COMPARATIVE ENERGY AND COST ANALYSIS BETWEEN CONVENTIONAL HVAC SYSTEMS AND GEOTHERMAL HEAT PUMP SYSTEMS

THESIS

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Abstract

To sustain the United States current affluence and strength, the U.S. Government has encouraged energy conservation through executive orders, federal and local laws, and consumer education. A substantial reduction in U.S. energy consumption could be realized by using geothermal heat pumps to heat and cool buildings throughout the U.S., though initial installation cost are a deterrent.

This thesis uses Monte Carlo simulation to predict energy consumption, life cycle cost and payback period for the vertical closed-loop ground source heat pump (GSHP) relative to conventional heating ventilation and air conditioning (HVAC) systems: air-source heat pumps (ASHP), air-cooled air conditioning with either natural gas, fuel oil, or liquid petroleum gas furnaces, or with electrical resistance heating. The Monte Carlo simulation is performed for a standard commercial office building within each of the 48 continental states.

Regardless of the conventional HVAC system chosen, the simulation shows that for each state the GSHP has the highest probability of using less energy and having a lower operating and life cycle cost than conventional HVAC systems; however, initial installation cost are typically twice that of conventional HVAC systems and payback periods vary greatly depending on site conditions. The average 50th percentile GSHP payback period in the U.S. was 7.5 years compared against the ASHP and 9.2 years compared against the air-cooled air conditioning with natural gas furnace. However, these values vary greatly depending on location and are most sensitivity to ground thermal conductivity, utility prices, and HVAC efficiency ratings. Under the right conditions, payback for GSHP systems can be much shorter and the model developed in this research can help predict energy savings and payback periods for a given site.

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I. Introduction

General Issue

Increasing world population, along with high energy consumption, continually drains the supply of fossil fuel energy. Although the United States represents only 4.7% of the world's population, it consumes nearly 25% of the world's fossil fuel resources (Pimentel and Rodriques, 1994). Within the next 60 years, it is estimated that the U.S. population will double, thus further reducing the supply of non-renewable fossil fuels (USBC, 1992).

During the year 2000, the United States consumed a record 99.3 quadrillion BTUs (British Thermal Units) of energy, of which 93% was from depletable fossil fuels (DOE, 2001). If the current consumption rates continue without policy changes, the United States will lack the resources to meet the high demand for energy in the future (Bush, 2001). Figure 1 depicts the total U.S. energy consumed by source in 2000.

Renewable energy sources such as hydropower, biomass, geothermal, solar, and wind provide only 7% of the total energy needs of the United States (DOE, 2001). It is critical that the U.S. utilize renewable energy sources and conservation measures to promote sustainability, strengthen the Nation's energy security, and increase the U.S. industrial competitiveness (Marley, 1995). Another important benefit of using renewable energy is that it may reduce carbon

dioxide emissions and other pollutants that contribute to acid rain, urban smog, and water pollution (Sissine, 1999).

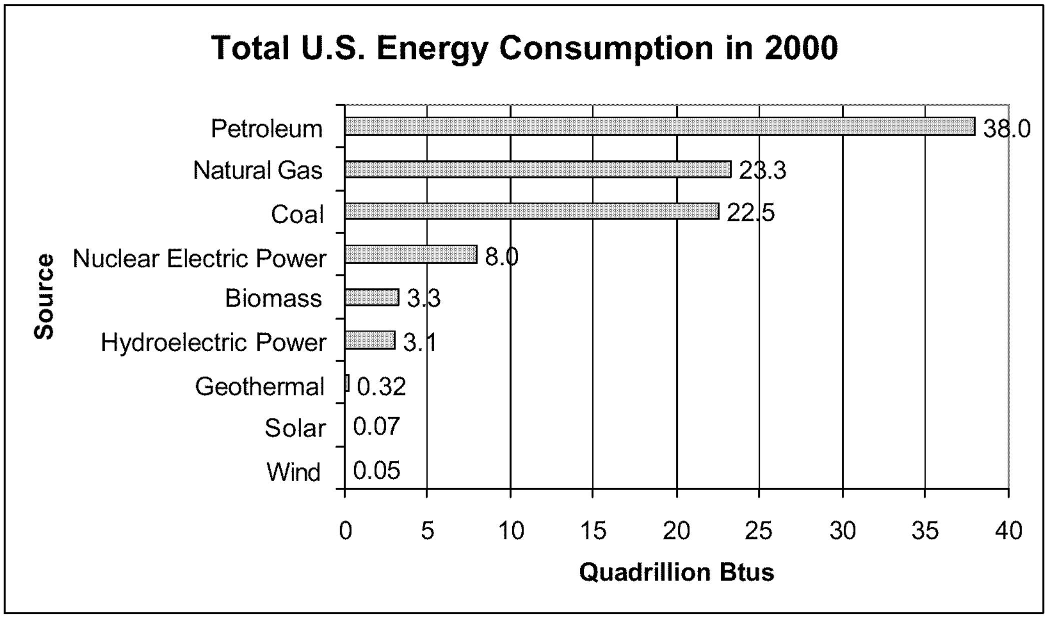


Figure 1. Total U.S. Energy Consumption by Source (DOE, 2001)

Approximately 13.5% of the total energy consumed in the U.S. is attributed to heating and cooling over 101 million homes, nearly 4.6 million commercial buildings and approximately 23,000 industrial manufacturing facilities. Studies conducted by the Department of Energy (DOE) indicate that Heating Ventilation and Air-Conditioning (HVAC) devices consume 8.4 quadrillion Btus (8% of total) per year in residential applications, 4.2 quadrillion Btus (4% of total) per year in commercial buildings, and a minimum of 0.7 quadrillion Btus (1% of total) per year in industrial manufacturing facilities (DOE, 2002). Furthermore, HVAC devices consume the largest percentage of total energy in residential and commercial buildings as shown in Figure 2. Significant fossil fuel

based energy savings could result from the use of more efficient heating and air-conditioning systems, such as Geothermal Heat Pumps (GHP).

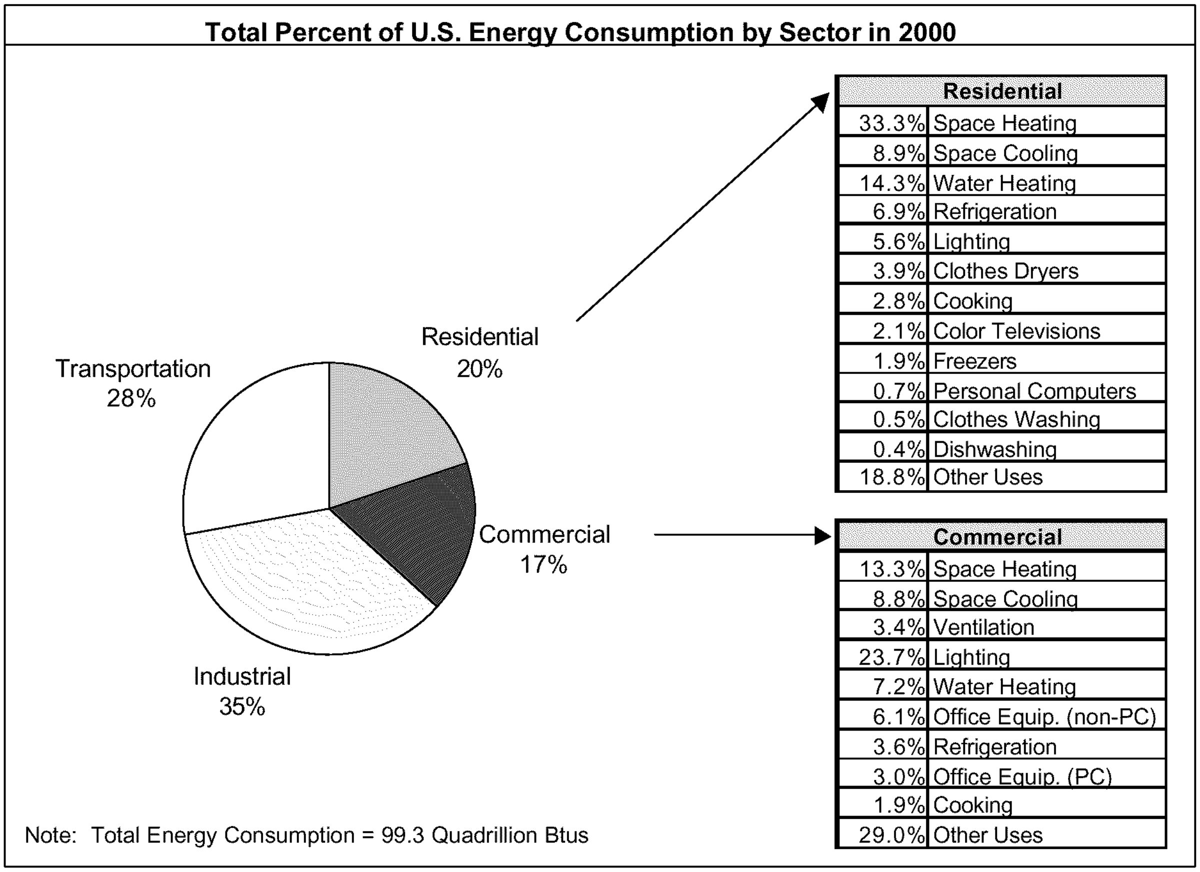


Figure 2. Total Percent of U.S. Energy Consumption by Sector in 2000 (DOE,2002)

Legislation

The U.S. Federal Government is the largest consumer of the nation's energy; given it's authority and size, it has an enormous role and impact in reducing energy consumption and invoking renewable technologies. Through legislation, the Federal Government has tried to inspire energy savings. The National Energy Policy states that energy conservation, repairing and modernizing energy infrastructure, and increasing environmentally sound energy

supplies, will provide national security, a healthy economy, and a high standard of living (Bush, 2001). To implement this policy, recent legislation has encouraged the enhancement of energy efficient technologies and used tax incentives to influence the use of renewable energy technologies.

Energy Policy Act

The Energy Policy Act of 1992 (EPACT) established national goals to increase material and equipment energy efficiencies and reduce fossil fuel use by encouraging commercialization of renewable energy and implementation of energy efficient technology (Public Law No. 486). EPACT requires that governmental projects be selected based on those goals in conjunction with life-cycle cost and cost-effectiveness procedures. EPACT also provides an indefinite extension of the 10% business tax credits for solar and geothermal equipment and specifically encourages states, municipalities, counties and townships to use geothermal heat pump applications.

To achieve energy conservation, EPACT requires all states to adopt energy codes that meet or exceed the requirements of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the Illuminating Engineering Society of North America (IESNA) Standard 90.1. ASHRAE/IESNA Standard 90.1 provides minimum requirements for energy efficient designs of commercial buildings. EPACT also requires that the DOE evaluate any revisions to Standard 90.1-1989 with the authority to obligate states to update their codes if accepted by the DOE. Currently, 32 states have conformed to Standard 90.1-1989, 10 states have adopted the revised Standard

90.1-1999 (not yet enforced by the DOE), and 8 states have adopted other standards equal to or more stringent than those of Standard 90.1 (BCAP, 2001). The minimum HVAC efficiencies established by Standard 90.1 will be discussed later in this document.

Executive Order 13123

In June of 1999, the Clinton administration issued Executive Order (EO) 13123, "Greening the Government Through Efficient Energy Management" (Clinton, 1999). This EO requires the federal government to meet certain renewable energy goals and provides guidance to meet these goals. Among other requirements, it mandates the use of life-cycle and cost-effective measures to reduce energy consumption per gross square foot of all its facilities (except those mentioned in Sec. 203) by 30% by 2005 and 35% by 2010 relative to 1985 consumption rates. Industrial and laboratory facilities are required to reduce energy consumption per square foot by 20% by 2005 and 25% by 2010 relative to 1990.

To help promote this decrease in consumption rates, EO 13123 encourages every federal agency to increase their use of renewable energy through purchasing electricity from renewable energy sources and funding renewable energy projects. The Secretary of Energy has established a goal that 2.5% of the total energy consumed by the federal government should consist of renewable energy sources by 2005. If met, this goal will equate to 4.6 trillion Btus of electricity annually (Clinton, 1999). Throughout the EO, stress is placed on the importance of using life-cycle cost analysis as the criteria for making

decisions regarding the use of renewable energy sources. In fact, the EO directs federal agencies to select, “where life-cycle cost appropriate”, ENERGY STAR ® and other products that are in the upper 25% of energy efficiency.

Geothermal Overview

Geothermal refers to the heat (thermal energy) that exists within the earth’s crust (geo). The dominant heat source for this internal energy is radioactive decay within the earth (Bullard, 1973). Geothermal technology can be used to produce electrical power and for direct heating/cooling of buildings, water heaters or industrial processing (ASHREA, 1991). However, there are only a few locations (California, Nevada, and Utah) in the U.S. where conditions are favorable for electrical power generation (Mclarty and Reed, 1992). On the other hand, the use of geothermal energy for direct heating and cooling is a viable option for nearly every location.

Geothermal Electrical Power

Geothermal electrical power plants are normally located near tectonic boundaries where plates are moving apart and thus high subsurface temperatures are in closer proximity to the earth’s surface (ASHRAE, 1991). In sites without adjoining tectonic plates, the temperature generally increases by approximately 13.7°F/1000 ft of depth (ASHRAE, 1991). Because geothermal electrical power plants need temperatures greater than 300°F, it is not uncommon for a plant to drill over a thousand feet to obtain the necessary hot

steam or water, even if the plant is near a site with adjoining tectonic plate movement (ASHARE, 1991).

Due to the geology of the United States and the location of tectonic plates, only parts of the west coast are prime locations for geothermal power plants. Some countries have a greater opportunity to harness this energy based on their relation to tectonic plates. Iceland, for example, is split directly in half by the Northern American plate and Eurasian plate. This unique situation gives Iceland the ability to utilize a larger percentage of renewable energy per capita than any other country. Seventy percent of Iceland's total energy demand is met by renewable energy with 50% of all Iceland's energy being from geothermal sources (Landsvirkjun, 2000). These figures are notable when compared to the United States total renewable energy use of 7% with only 0.3% of the total U.S. consumption of energy being from geothermal sources in 2000 (DOE, 2001).

Geothermal Heat Pump Technology

At depths of 15 feet and greater below ground level, temperatures remain relatively constant at around 55°F regardless of the outside ambient air temperature. This constant temperature exists nearly everywhere, and can be used by a GHP to heat and cool facilities (DOE, 1994). GHPs function as a heat exchanger by circulating fluid, within a buried pipe, between the ground and a building. During the winter, the heat from the ground is transferred to the fluid in the pipes; it is then compressed to a higher temperature and delivered to the air handler unit within the building where a fan transfers the heat from the piping coil to the supply air. During the summer, the system is reversed and the heat from

the building is transferred to the ground. A more in-depth explanation of this process will be discussed later.

Although consumers view GHPs as a recent technology, it has been effectively used in residential and commercial applications for over 30 years (Vukovic, 1996). The DOE's Federal Energy Management Program (FEMP) estimates that more than 400,000 GHP units were installed in the United States in 2000. These GHP units have been installed in houses, schools, businesses, state capitals, and several military installations.

Fort Polk Army Base, Louisiana, recently converted 4003 military family houses to GHPs using a 20 year Energy Savings Performance Contract (ESPC). Under an ESPC, private energy service companies identify energy savings potential of government buildings and then pay for the installation, operation, and maintenance of more energy efficient equipment. The resulting utility cost savings is then paid to the company until the contract expires. (A-GRAM 99-23, 1999) Under Fort Polk's ESPC, other energy efficient measures were also implemented, such as low flow hot water outlets, attic insulation and compact fluorescent lights. Prior to the conversion, natural gas furnaces with a central air-conditioner or an air-source heat pump were used. Total electric energy savings of 87.3 billion Btus a year, or 32.4% of the pre-retrofit electrical use, have been reported for the base. The elimination of the natural gas furnaces, in conjunction with the natural gas conserved by using the GHPs for supplemental domestic hot water heating, saves 26 billion Btus (260,000 therms) of natural gas a year. (Shonder and Hughes, 1997) Of the total energy conserved, 30% is attributed to

space heating and cooling of GHPs, 36% to supplemental hot water heating provided by GHPs, 29% to lighting retrofits, and 5% to low-flow shower heads (Shonder et al., 1998).

Another recent study evaluated the HVAC energy consumption records of 18 different schools in Lincoln, Nebraska. The results showed that schools using GHPs consumed 17% less total energy, and had a 5% lower maintenance cost per year then the next best conventional HVAC system. The schools with GHPs also had 15% lower life-cycle cost than the next most attractive option (based on 20 year evaluation period) than the best alternative. (Shonder et al., 2000)

An EPA study reports that GHPs have the lowest life-cycle cost of all other conventional HVAC systems and the least impact on the environment. Depending on location, GHPs can reduce carbon dioxide emissions by 23-44% compared to air source heat pumps and reduce electrical consumption by 63-72% compared to electric resistance heating/standard air conditioning equipment (EPA, 1993). Secretary of Energy, Bill Richardson, estimates that by 2005 the U.S. government will save as much as $700 million dollars a year through energy savings provided by GHPs (Denton, 1999).

GHP installation costs are relatively high due primarily to the expense of borehole drilling for the ground piping network and the lack of qualified GHP installers (Dooley, 2001). It is reported that the initial cost is recovered within three to five years due to the low operating and maintenance expenses of GHPs (Vukovic, 1996; Cengel and Kanoglu, 1998). Below is a list of the acclaimed benefits of GHP over conventional heating and air-conditioning systems. This list

was gathered from a collection of journals, DOE letters, and manufacturer advertisements:

-Lower operating cost: High efficiencies save 30-60% on utility bills
-Low maintenance: High reliability
-Comfortable: Relatively constant earth temperatures provide heating and cooling with no blast of hot or cold spots
-Renewable: Less dependency of fossil fuels
-Versatile: Compatible with nearly any home or business, regardless of terrain or weather conditions
-Economical water heating: Excess heat is used for water heating
-Saves space: The units provide heating and central air conditioning from the same unit; therefore, no outside condenser or mechanical room furnace is needed
-Safe and clean: No furnace is required and, thus, no flames, flue, odors, or additional fire sprinkler protection
-Environmentally friendly: Reduces carbon dioxide pollution during operational life-cycle
-Quiet and attractive: Requires no noisy and unattractive outside condensing unit.

Monte Carlo Simulation

Most energy and cost models are based on deterministic methods that assign a single value for each input variable, and thus a single output is computed. This output does not account for the variability or uncertainty associated with the input variables. To account for the variability and uncertainty, a probabilistic technique such as Monte Carlo simulation can be used (Clemen, 1996). In Monte Carlo simulations, input variables are given a range of possible values and an associated probability distribution. When the simulation is run, a range of possible outcomes, the chance of their occurrence, and an understanding of the influence that each input variable has on the output are provided (Finley and Paustenbach, 1994). The application of Monte Carlo simulation has been successfully used and accepted in a variety of fields, such

as pavement cost (Herbold, 2000) and human health risk assessments (Copeland et al., 1994). The goal of this modeling process is to give the decision maker more insight to the problem in order to make a more informed decision (Ragsdale, 2001). This simulation yields a better picture of reality by simulating real world behavior through use of variable distributions as opposed to deterministic point values (Crystal Ball, 1996).

The Monte Carlo simulation performed in this study uses Crystal Ball 2000 software from Decisioneering Incorporated, in conjunction with Microsoft Excel. The Crystal Ball software randomly selects input variables within the specified distribution for each of the parameters. These values are then used in the equation of interest to give a single output variable. The process is repeated thousands of times until the output probability distributions are unchanged by additional iterations (point of convergence); this typically occurs within 5,000 iterations (Copeland et al., 1993). This study will use 10,000 iterations to ensure convergence. When the analysis is completed, the model will give a range of possible outcomes in the form of a probability distribution for each output variable.

This study will first derive equations for the energy consumption, operating cost, life cycle cost, and payback period for each of the different types of HVAC systems. Appropriate probability distributions and ranges for each of the input variables will be determined. The Monte Carlo simulation will compute the expected outcome distributions for the energy, cost, and payback for each HVAC system in this study. This will enable a more comprehensive comparison

between systems. Finally, a sensitivity analysis will be performed on each of the input variables to determine which variables have the most influence on the outcome.

Research Objectives

The main purpose of this study is to evaluate and compare the energy consumption, life cycle cost, and payback periods of geothermal heat pumps to conventional heating ventilation and air conditioning (HVAC) systems. Using probabilistic modeling techniques, the analysis will address the following areas for each state in the U.S.:

1. Compare the annual energy consumption of GHPs (geothermal heat pumps) versus conventional HVAC systems.
2. Compare the annual operating and total life-cycle cost of GHPs versus conventional HVAC system.
3. Compare payback periods for each state based on site conditions, equipment efficiencies, local economics, and climatic conditions.
4. Provide a model to help decision makers understand the ramifications of using geothermal systems at a given site and determine which variables have the greatest influence to payback periods.

II. Literature Review

Overview

This study compares many different HVAC systems, thus it is important to understand the difference between them. This section begins by explaining the fundamentals of heating and cooling, followed by a discussion of the different conventional HVAC methods. The last half of this section discusses geothermal heat pump technology, the different types of geothermal heat pumps, and the advantages and disadvantages of each.

Heating and Air Conditioning Fundamentals

There are several methods to heat and cool a building, but the principles of each are the same. Table 1 lists the types of systems used for both heating and cooling. Note that heat pumps (air-source and geothermal) are used for both heating and cooling, whereas other systems are used exclusively for heating or cooling.

Table 1. Cooling and Heating Systems

COOLING	HEATING
Conventional Air-Conditioning System Air-Source Heat Pump (ASHP) Air-Cooled Water-Cooled	Conventional Heating Systems Air-Source Heat Pump (w/ backup elec. coil) Furnace (Natural Gas, Fuel Oil, or LPG) Electrical Resistance Heating Boiler (Hot Water or Steam)
Geothermal Heat Pumps (GHP) Closed-Loop (Ground or Water Source) Open-Loop (Groundwater or Water Source)	Geothermal Heat Pumps Closed-Loop (Ground or Water Source) Open-Loop (Groundwater or Water Source)

Air Conditioning Basics (Conventional and Geothermal)

The process of air conditioning is achieved by the refrigeration cycle depicted in Figure 3. In the cooling mode, the heat inside the building is transferred to the fluid-filled pipes and then released to the outside air. The fluid within the pipe is referred to as refrigerant. The refrigeration cycle at each position in the figure are explained below.

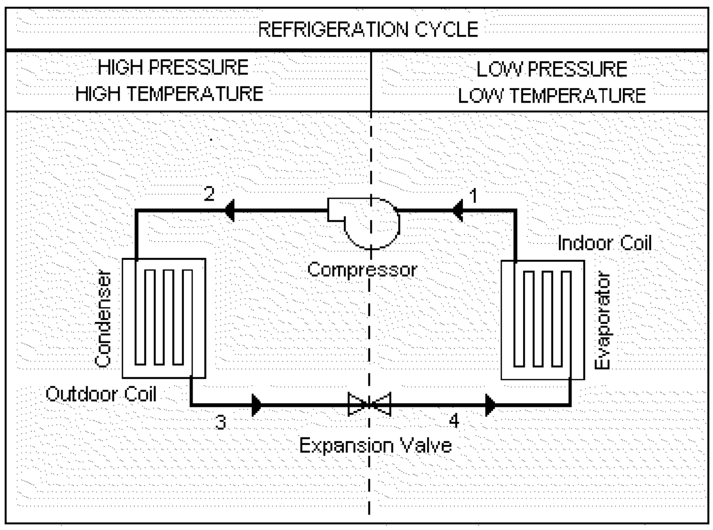


Figure 3. Air-Conditioning Refrigeration Cycle

Cooling cycle:

1. Cool low-pressure refrigerant vapor enters the compressor after absorbing heat from the air in the building. The compressor then compresses the cool vapor.
2. The refrigerant exits the compressor as a hot vapor under high-pressure, which then enters the condenser (or earth loop for geothermal heat pump systems). The loop condenses the vapor until it is mostly liquid.
3. The refrigerant then leaves the condenser (or earth loop) as a warm liquid. The expansion valve regulates the flow from the condenser so that only liquid refrigerant passes through.
4. The refrigerant expands as it exits the expansion valve and becomes a cold liquid. The liquid evaporates as it passes through the cooling coil (located in the indoor air handler unit). The refrigerant absorbs indoor heat from the air blowing over the coil surface and thus cools the building. The refrigerant is now a cool vapor and the cycle continues. (Cengel and Boles, 1994)

The evaporator is often referred to as the cooling coil and is located in the indoor air handler unit. A fan within the air handler unit blows air over the cooling coil and into the interior building space. The cooling coil size, and thus the size of the unit, depends on the cooling capacity needed within the building.

The condenser coil can be either air-cooled or water-cooled, as shown in Figure 4. Air-cooled coils are almost always used in residential and small commercial buildings. Air-cooled units simply use a fan to blow the heat from the coil and transfer it into the atmosphere. These units usually range from 1 to 50 tons, but can be as large as 1,000 tons (1 ton = 12,000Btu/hr). For large commercial buildings, water-cooled coils are normally used. Water-cooled units pass cold water over the hot condenser coil through the use of a shell and tube

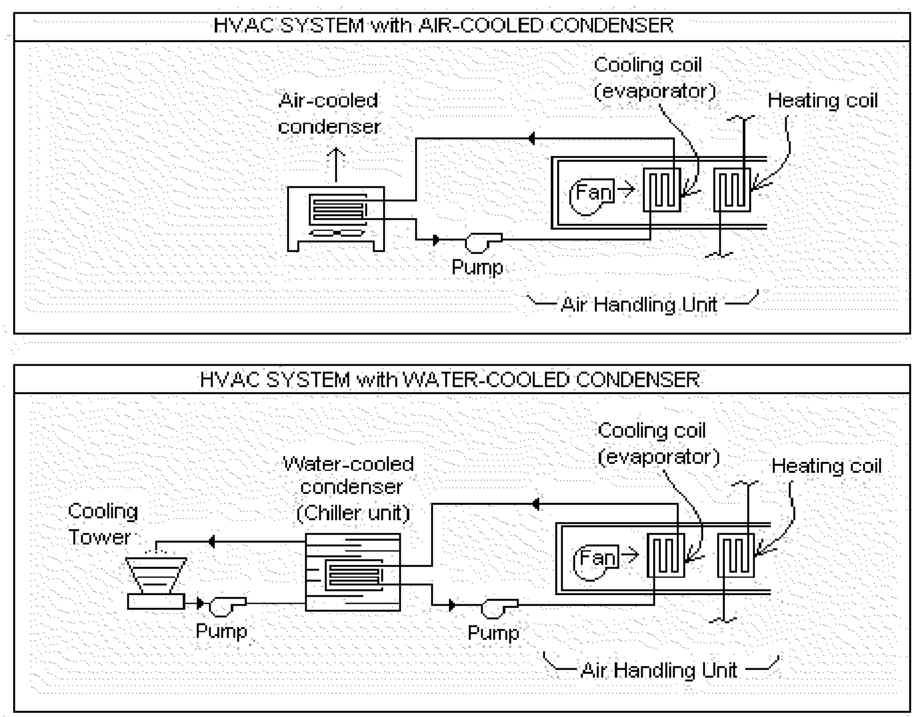


Figure 4. Typical System Designs for Air and Water Cooled Condensers

heat exchanger (chiller), thus transferring the heat to the water. Water-cooled chillers also require a water-cooling tower to cool the warm water that exits the chiller. Water-cooled units usually range from 50 to a 1,000 tons (McQuiston and Parker, 1994). The condenser coil size (and thus the condenser, or chiller size) is dependent upon the cooling load needed within the building.

Conventional Space Heating Systems

Boilers, furnaces, and electrical resistance heaters provide conventional space heating. For boilers, fossil fuel is burned to produce hot water or steam, which is sent to the heating coil within the air-handling unit. Furnaces burn natural gas, fuel heating oil, or liquid petroleum gas (LPG) in a chamber to heat an exchanger. Electric heaters use resistance rods to create heat directly in the air stream. The fan (or blower) within the air-handling unit moves air across these heat exchangers (hot water coil, furnace chamber, or electric calrods) and into ductwork to heat the building space. Boilers are typically used for larger buildings while furnaces, electrical resistance, and air-source heat pumps are found in smaller buildings. GHPs are used in both large and small buildings. (McQuiston and Parker, 1994)

Heat Pumps

Heat pumps use the same refrigeration cycle as the conventional air conditioning systems, shown previously in Figure 3. When in heating mode, a heat pump uses the same mechanical equipment but the direction of refrigerant flow is reversed. Figure 5 shows the heat pump flow cycle for the cooling and

heating mode. This is accomplished by the use of a reversing valve. When the flow is reversed, the indoor evaporator acts as the condenser and the outdoor condenser acts as the evaporator.

There are two types of heat pumps available: air-source heat pumps and geothermal heat pumps. Both systems work the same way but use a different medium to reject or absorb the heat. Air-source heat pumps expose the outdoor coil to the ambient air for heat transfer. Geothermal heat pumps place the outdoor coil within the earth, either buried in the ground or placed within a body of water such as a lake. The cooling cycle has already been discussed; therefore, only the heating cycle for the heat pump is described below.

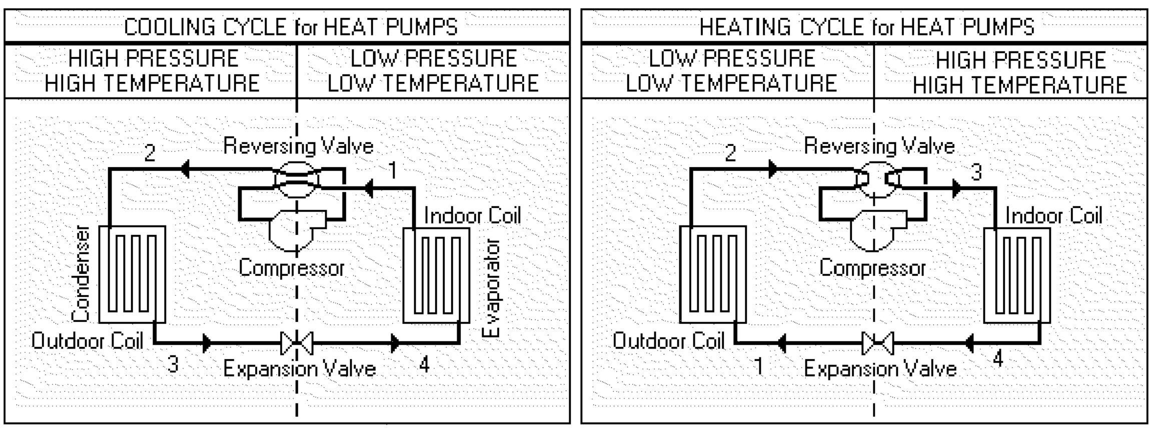


Figure 5. Heat Pump Cooling and Heating Cycles

Heat Pump Heating Cycle:

1. The refrigerant enters the outdoor coil as a cool liquid.
2. The cold liquid absorbs heat from its surroundings (air or geothermal earth source) and exits as a cool vapor. The cool vapor then enters the compressor.
3. The refrigerant exits the compressor as an extremely hot vapor, much hotter than the inside air. A fan blows over the hot coils to transfer the heat into the building.
4. The refrigerant leaves the indoor coil as a warm liquid and then enters the expansion valve to cool the liquid. (Cengel and Boles, 1994)

Air-Source Heat Pumps

Air-source heat pumps (ASHP) utilize the outside ambient air for a heat source during the winter and for a heat sink in the summer. These systems work best in locations that have mild winters and do not require a large heating load. The southern part of the United States is a good location for ASHPs. In places where the temperature frequently drops below 40°F, air-source systems can freeze and require a supplemental electrical resistant heater or a furnace, which drastically reduces the efficiency (Cengel and Boles, 1994).

Geothermal Heat Pumps

Although ambient air temperatures in the United States vary from minus 50 to 120°F (PRO-ACT, 1997), temperatures 10 to 15 feet below the ground surface remain relatively constant as shown in Figure 6. At the ground surface,

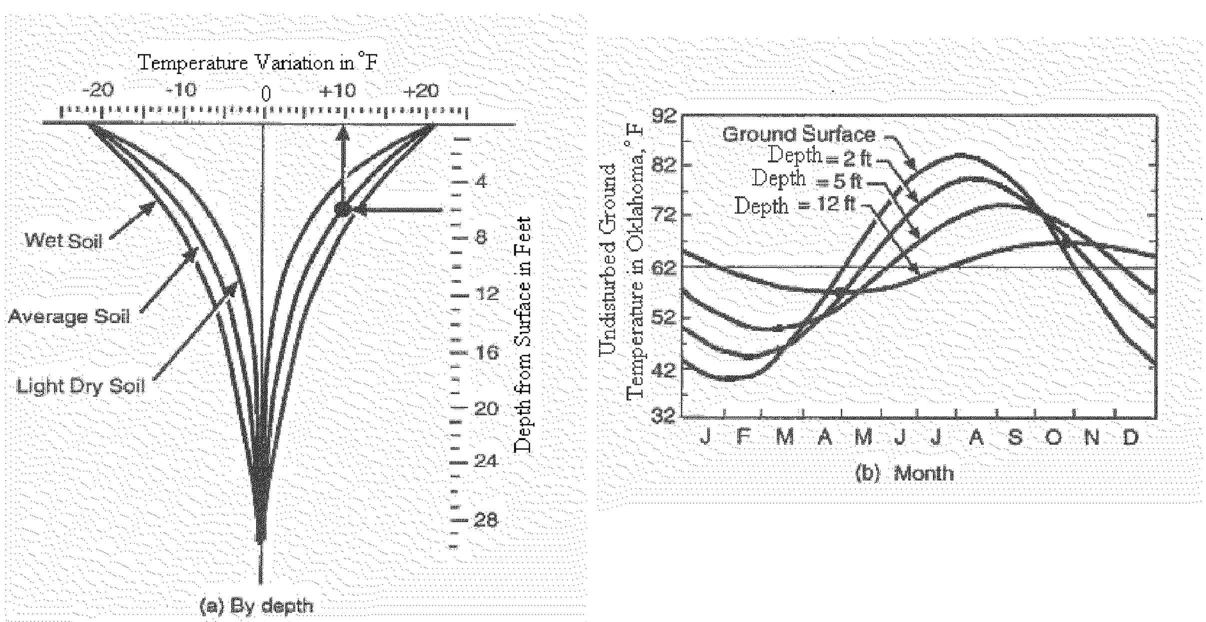


Figure 6. Soil Temperature Variations by Depth (a), by Month (b) (DOE, 1994)

temperatures fluctuate with the ambient air temperatures. With increasing depth, temperatures become more stable, until the temperature change with depth becomes negligible. The depth where temperature becomes very stable is approximately 28 ft as seen in Figure 6(a).

Depending on geographical location, the earth's annual temperature 15 ft below the surface ranges between 40-72°F, as seen in Figure 7. The relatively constant ground temperature allows the geothermal system to conserve energy when creating the desired indoor air temperature. This concept is explained best with the following example.

Scenario:

The ground temperature is 55°F, the desired indoor air temperature is 75°F, the outside temperature in winter is 10°F, and the summer temperature outside is 100°F.

Conventional temperature increase/decrease required:

Heating: 75° - 10° = 65°F
Cooling: 100° - 75° = 25°F

Geothermal temperature increase/decrease required:

Heating: 75° - 55° = 20°F
Cooling: 55° - 75° = NA

From this example, it is evident that conventional systems require greater energy to heat and cool spaces due to the large temperature difference that must be overcome. It is also interesting to note that during the cooling cycle, geothermal systems require only electric energy to transfer the heat from the building's air-handler unit to the ground loop as ground temperatures are normally lower than the desired inside air temperature.

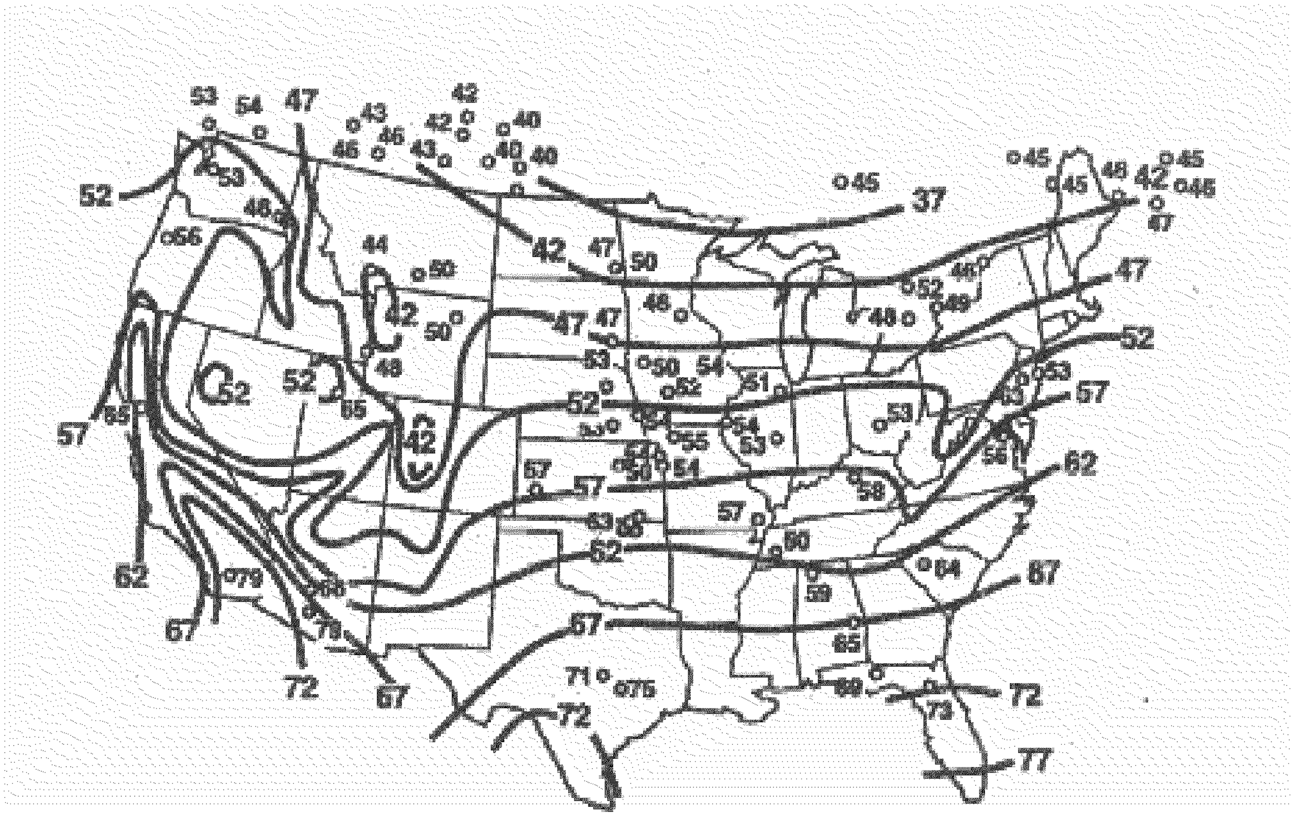


Figure 7. Mean Annual Earth Temperatures (°F), (DOE, 1994)

Several geothermal heat pump configurations exist because of different external heat exchange mediums and pipe orientations. The two types of geothermal heat pump systems are closed-loop and open-loop. The three types of mediums are ground, groundwater and water. The two types of pipe configurations are vertical and horizontal with either striate pipe or spiral (slinky) pipe. Figure 8 shows each of the possible geothermal heat pump systems.

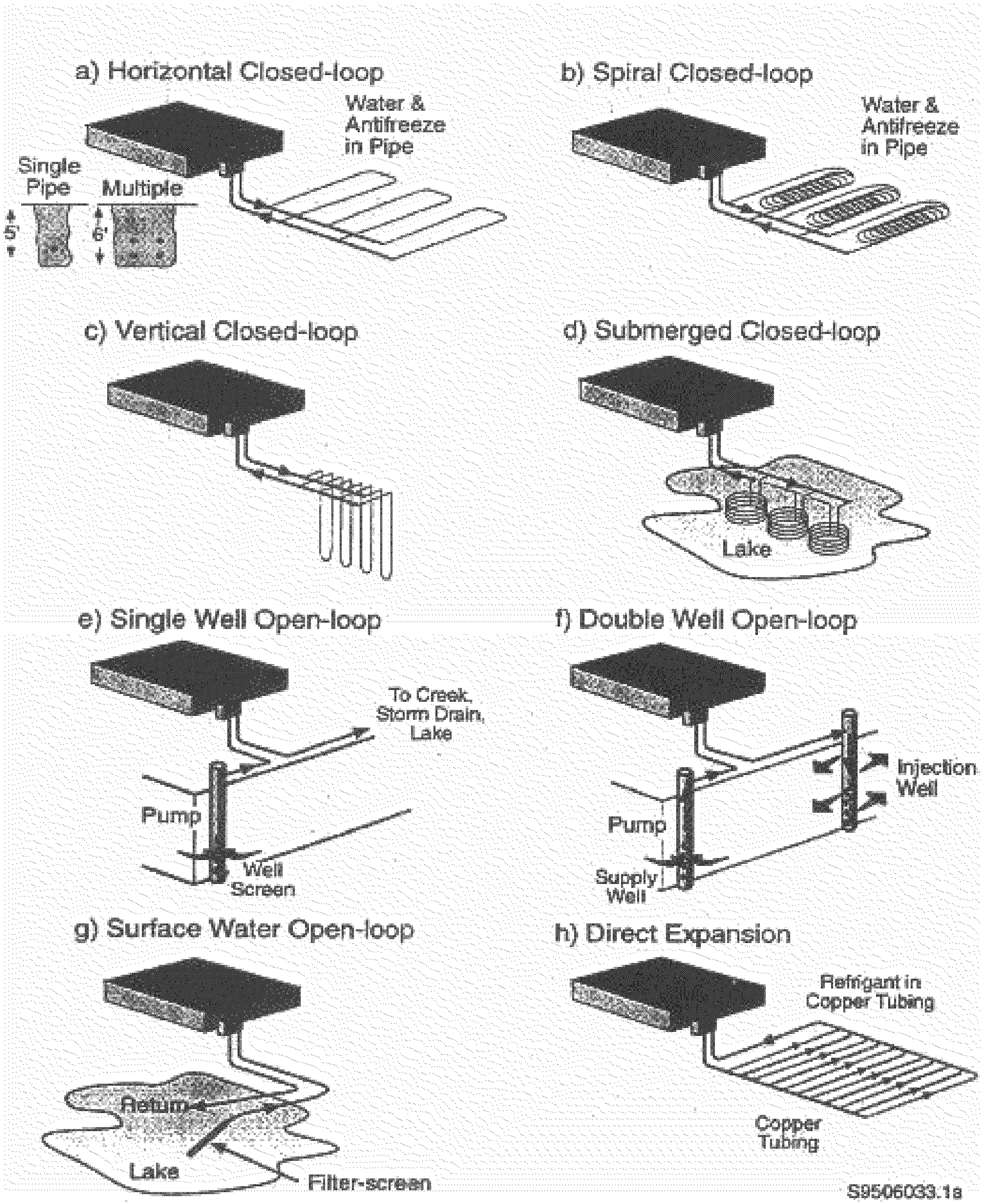


Figure 8. Geothermal Heat Pump Systems (DOE, 1994)

Closed-Loop Ground Source Heat Pumps (GSHP)

Closed-loop Ground Source (coupled) Heat Pump (GSHP) systems (see Figure 8(a) through 8(c)), are the most common type of geothermal heat pump used in the United States. GSHP systems typical range from 1.5 to 3 tons in residential applications. Commercial applications have included systems as large as 1,700 tons, as is the case in a New Jersey college where 400 vertical boreholes, 400 ft deep, were installed under a parking lot (Sachs and Dinse, 2000).

GSHP systems circulate fluid (water/antifreeze solution) through a series of buried pipes (loops) that exchange heat with the surrounding ground or groundwater. Total pipe length depends on the required heating or cooling load (whichever requires the longest pipe length). The greater the load, the longer pipe length required to provide adequate surface area for heat transfer. GSHP systems are generally installed with high density, polyethylene pipes with diameters typically ranging from 3/4 to 1-1/2 inches (Kavanaugh and Rafferty, 1997). Closed-loop GSHP can be configured vertically or horizontally. The ground thermal conductivity is perhaps the most important parameter when determining installation cost because it has the greatest influence on the rate of heat transfer, which is directly related to the pipe length required (DOE, 1994).

Vertical Closed-Loop GSHP Vertical GSHPs consist of a series of parallel loops (U-tubes) spaced approximately 20 feet apart (Sachs and Dinse, 2000). The required number of parallel pipes ultimately depends on the dominant heating or cooling load. Each parallel pipe is placed in a borehole

drilled to depths of 50 to 600 feet with a borehole diameter from 4 to 6 inches. Boreholes are typically backfilled with a bentonite and sand grout mixture, see Figure 9 (Kavanaugh and Rafferty, 1997). Appendix A depicts a top-down view of a vertical GSHP system along with alternative loop designs.

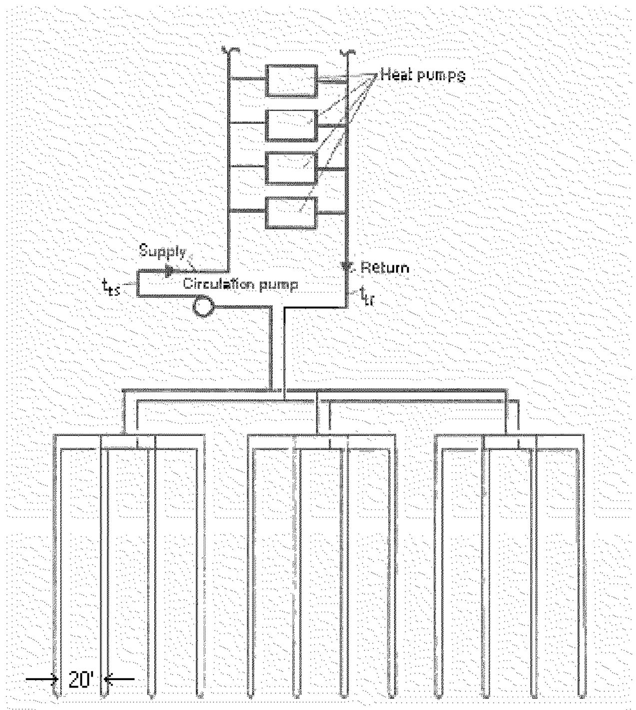


Figure 9. Closed-Loop Ground Source Heat Pump (GSHP), (ASHRAE, 1997)

State and local laws heavily regulate grout backfill requirements to seal the borehole. Twenty-eight states in the U.S. have regulations specifying allowable grouts and proper grouting techniques (Den Braven, 2000). These regulations are to ensure that groundwater and aquifer quality are not contaminated by pollutants that may seep through the vertical borehole penetrations. The regulations vary within each state and some counties, municipalities, and other jurisdictions may have additional regulations.

The most commonly used grouts for sealing boreholes include: neat cement, high solids bentonite, concrete, sand cement, cement or concrete bentonite, bentonite pellets or chips, cuttings, and thermally enhanced grout or sand–bentonite. Of these, only neat cement and high solids bentonite are accepted by nearly every state (Den Braven, 2000). The type of grout selected is very critical. Studies report that grouts with higher thermal conductivity will significantly shorten the required loop lengths. When using standard bentonite grout as a base case, a 10% reduction in pipe lengths is achievable by using thermally enhanced grout (Carlson, 2000) and a 33% reduction in pipe length can be obtained by using sand cement (Spilker, 1998). Also important is the depth to which the grout must be placed. State regulations typically require that at a minimum, the first 10 to 15ft of the borehole (from the ground surface) be backfilled with grout. This may be deeper depending on state and local regulations (Sachs and Dinse, 2000).

Horizontal Closed-Loop GSHP Horizontal loop systems are similar to the vertical loop system but do not require borehole drilling (see Figure 8(a)). Horizontal pipes are buried in trenches 4 to 10 feet deep and typically spaced from 6 to 12 feet apart. Typical lengths range from 100 to 400 feet depending on the soil characteristics. This system is attractive because it eliminates the expensive borehole drilling, but there are serious drawbacks. First, horizontal systems require much more land space to install. Second, the temperatures of the soil fluctuate with season and rainfall at shallow depths causing them to be less efficient (DOE, 1994).

Another typical horizontal closed-loop system is the spiral, or slinky, coiled pipe configuration (see Figure 8(b)). This configuration is attractive because it conserves land space, but it also requires larger pumps (DOE, 1994). Spiral piping systems yield 10% to 12% higher total pressure head losses than straight piping networks (Kavanaugh, 1998).

Because shallow ground depth temperatures vary with season, antifreeze mixtures are usually required for systems in colder regions. Antifreeze solutions are normally a mixture of 85% water and 15% antifreeze. Antifreeze solutions can vary but they typically consist of ethylene glycol, propylene glycol, methanol, ethanol, sodium chloride, calcium chloride, or potassium acetate. Each fluid has advantages and disadvantages with regard to toxicity, flammability, leakage, corrosion, and thermodynamic properties. A recent study rated propylene glycol as the best alternative, primarily due to its low risk to human health, fire, and the environment. The study further showed that ethanol actually required the least amount of energy to operate, but the energy savings were relatively insignificant compared to the other antifreeze solutions. The same study compared life-cycle costs for each fluid and found that potassium acetate had the highest cost, but the difference between them all was relatively small (Heinonen et al., 1997). State regulations are the primary driver for fluid selections. Approximately half of the states in the U.S. have regulations that specify acceptable loop fluids. Potable water is the only fluid that is accepted by all states. Of the states that have regulations, the most accepted fluids are propylene glycol and potassium acetate (Den Braven, 1998).

Open-Loop Ground Water Heat Pumps (GWHP)

Open-loop Ground Water Heat Pump (GWHP) systems use the local groundwater directly as the heat transfer medium (see Figures 8(e) and 8(f)). In residential and small commercial applications, groundwater is pumped directly through the pipes to the heat pump. In larger commercial applications, groundwater is pumped to an intermediate water-to-water plate heat exchanger. Through the plate heat exchanger, heat is absorbed (or rejected) from the groundwater to the building water loop without mixing the two fluids. This separate water loop then circulates to the heat pumps within the building (Rafferty 1998) as shown in Figure 10. The plate heat exchanger is used to eliminate pipe fouling and corrosion (caused by poor groundwater quality) from entering the building's piping network (Kavanaugh and Rafferty 1997).

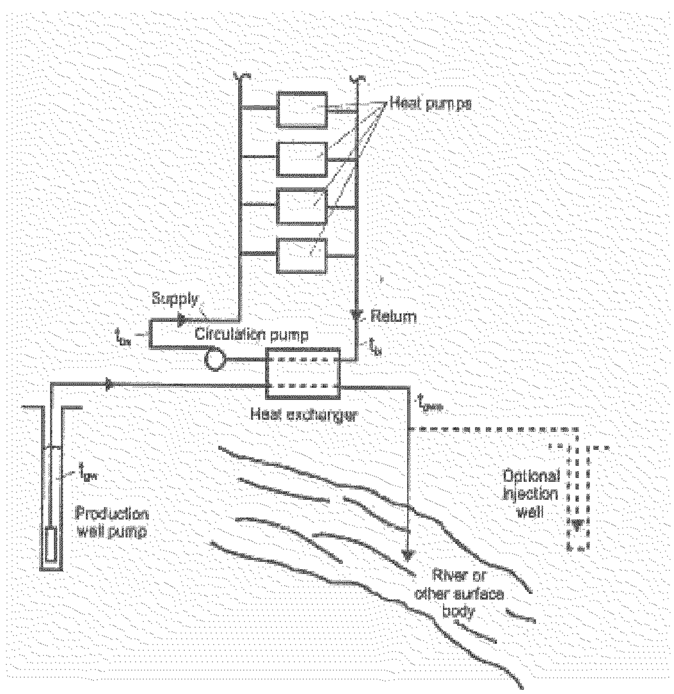


Figure 10. Open Loop Ground Water Heat Pump (GWHP), (ASHRAE, 1997)

GWHPs are an excellent alternative to GSHPs, assuming a large volume of easily pumped groundwater exists at the site. If installed correctly, GWHPs cost considerably less then closed-loop systems. The GWHP uses very little ground surface area and a relatively inexpensive well. A single well can often support an entire building (Sachs and Dinse, 2000). After heat is transfer from the groundwater to the building loop, the groundwater is disposed of by means of an injection well or emptied into a body of water such as a lake or river. State regulations often dictate accepted disposal discharge methods. If available, discharge to an existing water body is less expensive than injection; however, the possibility of well water drawdown must be evaluated. Injection well disposal costs are considerably higher, but drawdown concerns are reduced (Kavanaugh and Rafferty, 1997).

Surface Water Heat Pumps (SWHP)

Surface Water Heat Pump (SWHP) systems can be either open or closed loop. SWHPs operate in the same manner as the open-loop GWHP and closed-loop GSHP systems with the difference being the heat transfer medium (see Figures 8(d) and 8(g)). SWHPs utilize open bodies of water such as ponds, lakes or rivers. Caution must be used with these systems because they are subject to wide seasonal temperature variations and may cause ecological concerns.

Direct Expansion (DX) Ground Coupled Heat Pumps

DX GCHPs consist of horizontal closed-loop copper piping usually filled

with R-22 refrigerant (see Figure 8(h)). DX GCHPs are different from GCHPs because they circulate the R-22 refrigerant in the ground loop and directly use that loop within the heat pump unit. With the previously mentioned GCHPs, water/antifreeze solutions flow through the ground loop and the heat is transferred to a different refrigerant loop within the heat pump unit. This subtle difference yields higher heat transfer characteristics for DX GCHPs (DOE, 1994). However, very few states allow this application because the systems may leak the refrigerant into the ground (Den Braven, 1998). Another disadvantage is that the copper piping is subject to corrosion (DOE, 1994).

Geothermal Hot Water Heating

Heat pumps are often manufactured with an add-on feature that provides supplemental domestic water heating, commonly referred to as desuperheaters. This is accomplished by using the excess heat from the heat pump's compressor to heat the water within the hot water tank. Thus, virtually no additional furnace energy is required to produce hot water during the summer months and less furnace energy is needed during the winter months. Fort Polk's military family housing project reports a 71% reduction of energy use for water heating by the addition of the desuperheaters in conjunction with low flow rate shower heads (Shonder et al., 1998).

III. Methodology

Modeling Assumptions

The main research objectives are to evaluate the payback periods and life cycle cost of each HVAC system for each state. These two objectives are obtained by evaluating the annual operating cost, annual energy consumption, and initial installation cost. Another objective is to determine how much each input variable influences the outcome. Figure 11 displays the methodology flow diagram developed to evaluate these objectives.

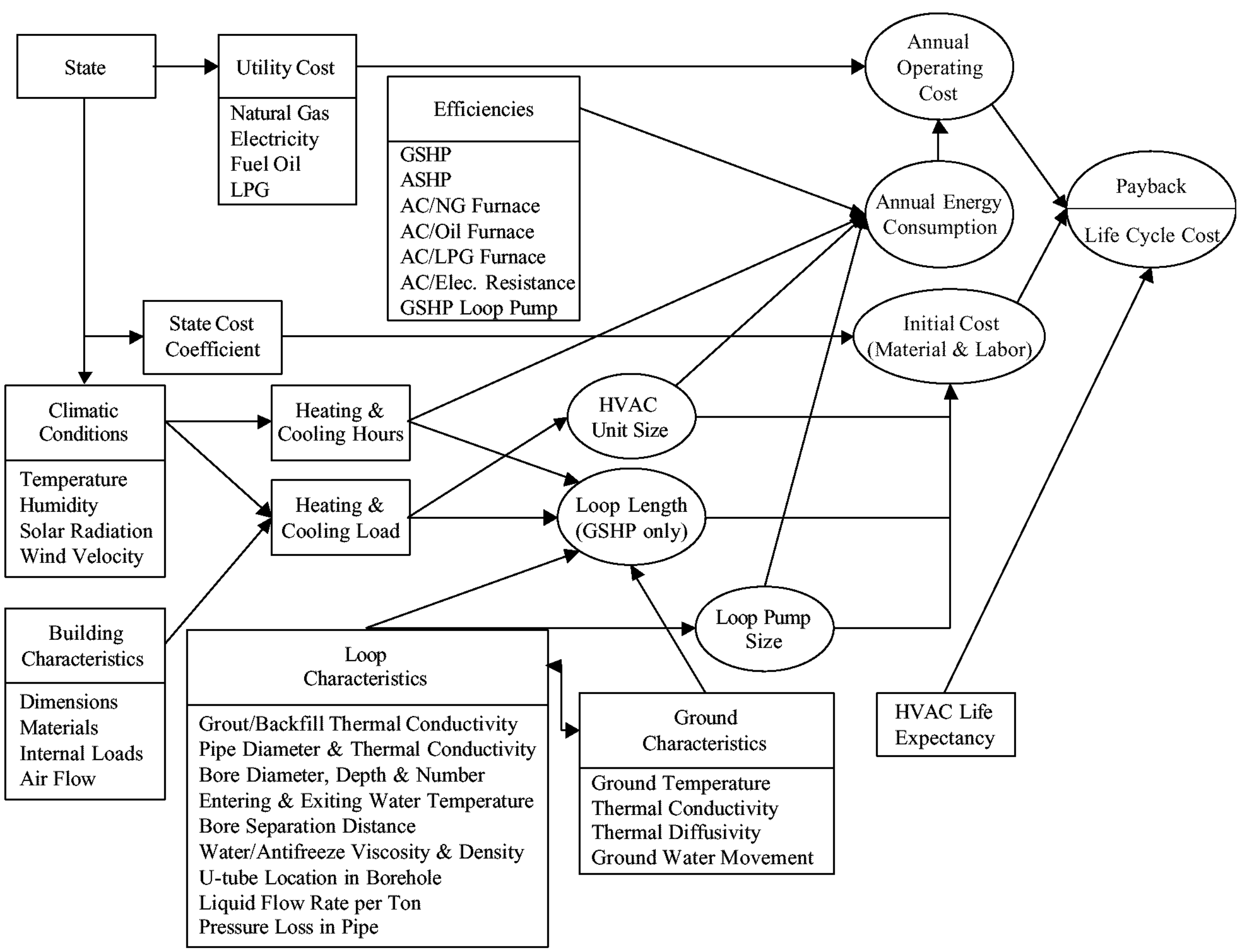


Figure 11. Methodology Flow Diagram

The process begins by selecting a U.S. state for analysis. The state chosen will determine the utility prices, material and labor cost coefficients, and climatic data. Climatic data, with the building characteristics, is used to determine the heating and cooling hours and the heating and cooling loads. Heating and cooling loads determine the HVAC unit size (capacity). The heating and cooling loads/hours, loop characteristics, and ground characteristics determine the loop length and loop pump size needed. Loop and ground characteristics have many interdependencies within them, i.e., pipe diameter and water/antifreeze properties determine liquid flow rates which contribute to pressure losses, entering and exiting loop water temperature, and loop pump size.

The initial installation cost is computed based on each state's material and labor cost for the HVAC unit size, loop length, and loop pump size. Annual energy consumption is dependent on the heating and cooling hours, efficiency and size of the HVAC unit and loop pump. Annual operating cost is based on the utility price and the annual energy consumption. Life cycle cost is derived from the annual operating cost, the installation cost, and the life expectancy of each system. The final output parameter is the payback period of geothermal systems relative to conventional HVAC systems, thus encompassing all of the input variables within the model.

Systems Selected for Monte Carlo Simulation

Several systems can be used to heat and cool spaces, as was seen in Table 1. This study will consider only those methods used for conditioning small

commercial and residential spaces where cooling and heating loads are less than 6 tons; therefore, water-cooled air-conditioning systems (chiller with cooling tower) and boilers (hot water or steam) will not be evaluated. The closed-loop water source heat pump, open-loop groundwater heat pump, and open-loop water source heat pump all require a water medium that may be unavailable to the majority of consumers and will therefore not be evaluated. The horizontal configuration will not be evaluated because it requires large land areas which also may be unavailable, and its sensitivity to climatic changes causes it to behave similar to the air-source heat pump (DOE, 1994). This model will focus on the vertical closed-loop ground source heat pump broadly accepted at most U.S. locations. Table 2 lists the six systems that will be compared in this study.

Table 2. HVAC Systems for Comparison

SYSTEM	Abv.
Vertical Closed-Loop Ground Source (Coupled) Heat Pump	GSHP
Air Source Heat Pump	ASHP
Air-Cooled air-conditioning with Natural Gas Furnace	AC/NG
Air-Cooled air-conditioning with Fuel Heating Oil Furnace	AC/Oil
Air-Cooled air-conditioning with Liquid Petroleum Gas Furnace	AC/LPG
Air-Cooled air-conditioning with Electrical Resistance Heater	AC/Elec

Note: Liquid Petroleum Gas (LPG) furnaces typically consist of 90% propane and thus are often referred to as propane furnaces. Natural Gas (NG) furnaces typically consist of 95% methane. (Czarick and Lacy, 2001)

Heating and Cooling Loads, Hours, and Building Characteristics

Heating and cooling loads depend on building construction materials, building dimensions, internal loads (people, equipment, lighting), and climatic data (solar radiation, humidity, outdoor air temperatures, wind velocity, etc.). HVAC systems are then sized based on the heating and cooling load needed

during the most extreme weather conditions for the location. To compare each system listed in table 2, a typical 2,000 square foot commercial office building with approximately 10% fresh outside air ventilation is assumed (see Appendix B for building characteristics). This study uses Trane's Trace 700 software to compute the heating and cooling loads of an office building for 78 cities within the United States. The analysis uses city-specific weather values from a typical meteorological year.

Each state's design heating and cooling load is estimated by the results obtained for multiple cities within that state. The cities used to represent each state are listed in Appendix C. The computation is first performed for the most populated city within each state. Other cities were then chosen based on their location within the state to better represent the broadest range of loads possible within each state. For example, the heating and cooling loads for the state of Texas are based on calculations from Houston, San Antonio, Dallas/Fort Worth, Lubbock, and Corpus Christi. From these cities, the distribution for the heating and cooling load is obtained by using the city that has the lowest maximum load and the city that has the highest maximum load. This range is then modeled as a uniform distribution, meaning the load has an equal probability of being any value within the minimum and maximum range for that state. To account for additional uncertainty in the model, the minimum and maximum loads were also given a ± 10% variance. The minimum and maximum heating and cooling loads used for each state are listed in Appendix D.

Knowledge of annual hours required to heat and cool the office is crucial to the calculation of energy consumption within each state. The Air Conditioning and Refrigeration Institute (ARI) and the Gas Appliance Manufactures Association (GAMA) have developed estimated minimum and maximum cooling and heating hours within each state. The cooling and heating hours represent the annual hours that a HVAC unit is required to operate at a given load during a typical year. Appendix D contains each state's range of annual heating and cooling hours used for this study.

Annual Energy Consumption

The annual energy consumed by HVAC systems (net energy input) is a function of the annual output energy and the efficiency of the unit as shown in Equation 1. The output energy, E_{out}, represents the maximum design-heating (or cooling) load (Btu/hr) multiplied by the annual heating (or cooling) hours. It is assumed that all systems in this simulation operate with a single speed motor, which only cycles on or off. This assumption implies that the HVAC unit operates at full capacity when the unit is operating. From Equation 1, it is apparent that less input energy is required to operate the system with higher efficiencies.

$$E_{in} = \frac{E_{out}}{\eta * 3.415 \, {}^{Btu}\!/_{Whr}} \qquad (1)$$

where

E_{in} = Net Energy Input, Watt-hr (Whr)
E_{out} = Net Useful Energy Output (Btu)
η = Efficiency

The annual energy consumption is computed using the design heating and cooling loads, annual heating and cooling hours, and HVAC unit efficiencies. Equations 2 through 5 depict the formulas used to compute the Annual Energy Consumption (AEC) for each system in units of Watt-hours per year. The GSHP also includes the power necessary to operate the loop pump.

For Air Source Heat Pump (ASHP):

$$AEC = \frac{DCL * ACH}{SEER} + \frac{DHL * AHH}{HSPF} \tag{2}$$

For Ground Source Heat Pump (GSHP):

$$AEC = \frac{DCL * ACH}{SEER} + \frac{DHL * AHH}{3.415 \, {}^{Btu}\!/_{Whr} * SCOP} + \frac{LPW * (ACH + AHH)}{\eta_{motor}} \tag{3}$$

For Air Cooled AC with Furnace (AC/NG, AC/Oil, AC/LPG):

$$AEC = \frac{DCL * ACH}{SEER} + \frac{DHL * AHH}{3.415 \, {}^{Btu}\!/_{Whr} * AFUE} \tag{4}$$

For Air Cooled AC with Electrical Resistance (AC/Elec.):

$$AEC = \frac{DCL * ACH}{SEER} + \frac{DHL * AHH}{3.415 \, {}^{Btu}\!/_{Whr}} \tag{5}$$

where

AEC = Annual Energy Consumption (Watt-hr/yr)
DHL = Design Heating Load (Btu/hr)
DCL = Design Cooling Load (Btu/hr)
AHH = Annual Heating Hours (hr/yr)
ACH = Annual Cooling Hours (hr/yr)

LPW = Loop Pump Work (Watt)
SCOP = Seasonal Coefficient of Performance (unitless)
SEER = Seasonal Energy Efficiency Ratio (Btu/Watt-hr)
HSPF = Heating Seasonal Performance Factor (Btu/Watt-hr)
AFUE = Annual Fuel Utilization Efficiency (unitless)
COP = Coefficient of Performance (unitless)
η_{motor} = Loop Pump Motor Efficiency (unitless)
Note: Electrical resistance heating efficiency = 1, all input energy is directly used by the heating coils.

HVAC Efficiency

As previously mentioned, minimum commercial HVAC efficiencies are established by ASHRAE/IESNA Standard 90.1-1989, and enforced by EPACT. Table 3 depicts the minimum efficiency required by Standard 90.1 for each HVAC system. The table also depicts the efficiency notation used for each type of HVAC system (manufacturers typically advertise efficiencies using the same notation). For the HVAC systems compared in this study, the minimum efficiencies required by EPACT in the 1989 standard are the same as those published in the 1999 standard; thus, no addition constraints are needed for the 10 states that have adapted the 1999 standard. These efficiency values are the minimum efficiencies for each HVAC system's distribution; the remaining portion of the efficiency distributions for each system will now be discussed.

Table 3. Minimum Efficiency Ratings from ASHRAE/IESNA Standard 90.1

SYSTEM*	Abv.	Min Eff.	Units
Ground-Source Heat Pump (GSHP)			
Heating: Coefficient of Performance	COP	2.5	Unitless
Cooling: Energy Efficiency Rating	EER	10	Btu/Whr
Air-Source Heat Pump (ASHP)			
Heating: Heating Seasonal Performance Factor	HSPF	6.8	Btu/Whr
Cooling: Seasonal Energy Efficiency Rating	SEER	10	Btu/Whr
Air-Cooled Air Conditioning (AC)			
Cooling: Seasonal Energy Efficiency Rating	SEER	10	Btu/Whr
Furnaces (NG, Oil, LPG)			
Heating: Annual Fuel Utilization Efficiency	AFUE	78%	NA
Electrical Resistance Heaters (Elec)			
Heating: Coefficient of Performance	None	NA**	NA

* Minimum efficiency values are for split systems under 65,000 Btu/hr. (outdoor condenser with indoor air-hander)

** Electric resistance heaters are 100% efficient (input electricity is used directly).

The Air Conditioning and Refrigeration Institute (ARI) Unitary Directory maintains a database of manufacturers' listed efficiency ratings for all certified cooling units within the U.S. (ARI, 2000). This information was converted into a probability distribution and used in Crystal Ball (see Figures 12 and 13).

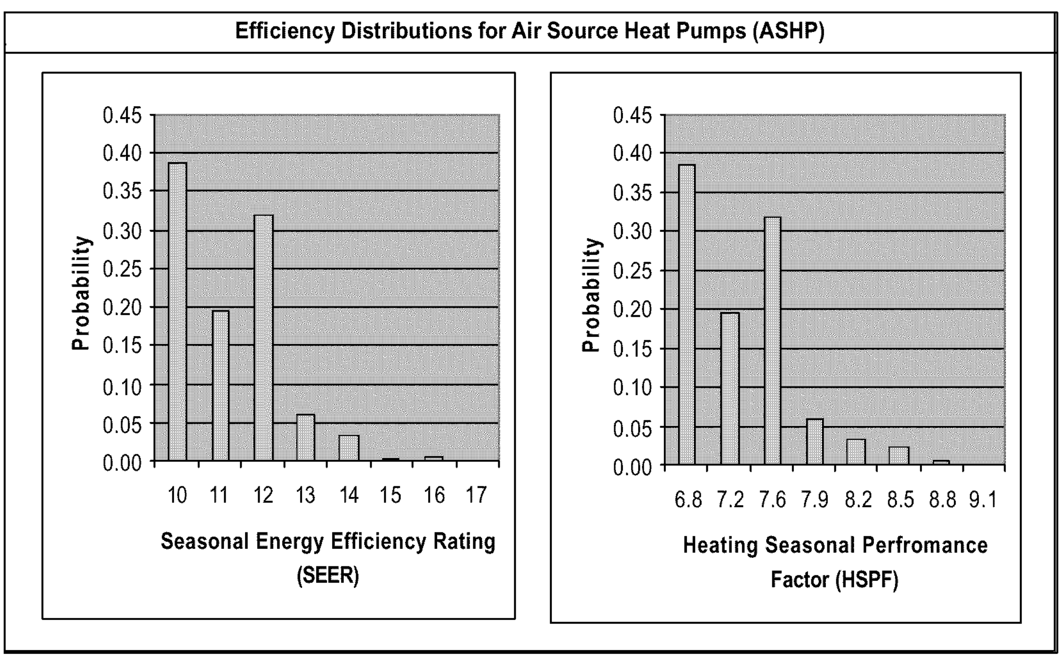


Figure 12. SEER and HSPF efficiency distributions for ASHPs

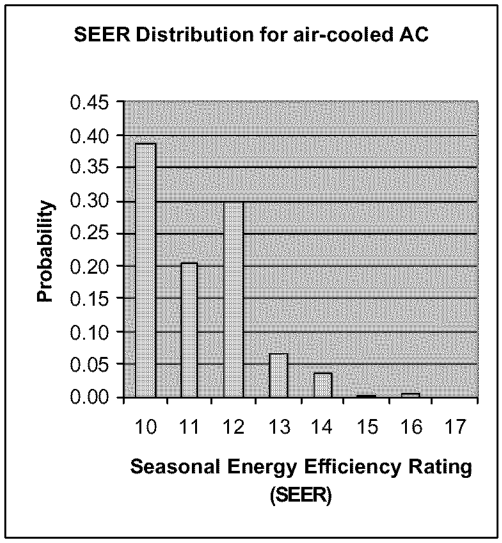


Figure 13. SEER distribution for air-cooled AC

ASHPs are rated under ARI 210/240 (ASHRAE/IESNA Standard 90.1, 1999) and are seasonal, meaning that the efficiency rating takes into account varying weather conditions and supplementary heating requirements. The Heating Seasonal Performance Factor (HSPF) is the total heating output (Btu/hr) of the ASHP during its normal annual heating period divided by the total electric power input (watt) during the same period. During the cooling season, air-conditioners and ASHPs are rated by Seasonal Energy Efficiency Ratio (SEER), which is calculated using the same method as the HSPF. These ratings are based on a moderate climate (Washington, DC) and thus do not reflect the exact efficiency performance of the ASHP within different states. However, the energy consumed by each HVAC system is differentiated by state because state specific climatic data is used (heating and cooling loads and hours).

The efficiency distribution for GSHPs was obtained for systems less than 72,000 Btu/hr (6 tons) by soliciting manufacturing performance specifications

from nine different manufacturers for a total of 195 units. Using JMP-4 statistical software package by SAS Institute Inc., the data is best fit using a lognormal distribution as shown in Figure 14.

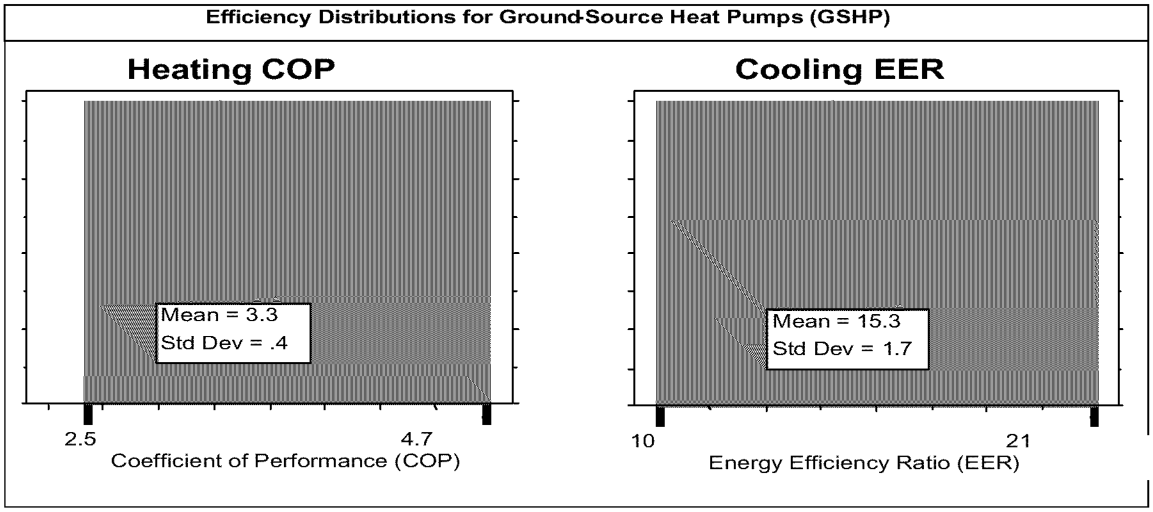


Figure 14. Lognormal distribution for COP and EER ratings of closed-loop GSHP

GSHPs are rated under ARI/ISO 13256-1 (ASHRAE/IESNA Standard 90.1, 1999), which is based on laboratory test conditions (heating and cooling entering loop water temperature of 32°F and 77°F, respectively), which may not represent actual performance. According to ASHRAE's GSHP design manual, "a reasonable assumption for seasonal efficiency of the [ground source] heat pump is 5% above the design conditions" (Kavanaugh and Rafferty, 1997). The Coefficient of Performance (COP) of the GSHP is calculated by dividing the total heating capacity provided (Btu/hr) by the total electrical input power (watts) x 3.412 Btu/watts-hr. The Energy Efficiency Rating (EER) of the GSHP is calculated by dividing the cooling capacity (Btu/hr) by the input power (watts).

The final efficiency distributions needed are for furnaces. The Gas Appliance Manufactures' Association (GAMA) tracks AFUE ratings for all certified gas and oil furnaces manufactured and sold within the United States. GAMA data lends itself to a triangular distribution for the AFUE ratings of both gas and oil furnaces using the minimum, maximum, and most likely AFUE ratings as shown in Figure 15 (GAMA, 2001).

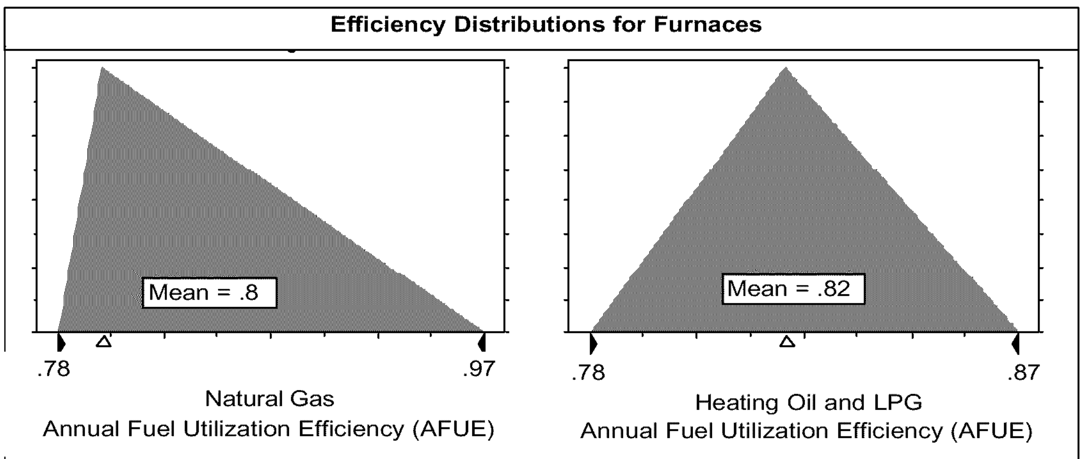


Figure 15. Triangular distribution for AFUE ratings of gas and oil furnaces

Ground Source Heat Pump Loop Length Solver

To accurately determine the start-up cost of the closed-loop GSHP, the length of the vertical ground loop is solved using the methodology recommended by the ASHRAE Ground-Source Heat Pump design manual (Kavanaugh and Rafferty, 1997). The GSHP loop length is dependent on over 30 input variable distributions. The loop length for the 2,000 square foot office building is calculated for both the cooling and heating season of each state and sized based

on the season that requires the longest loop length. The two fundamental equations for solving for the GSHP loop length are:

For cooling:

$$Lc = \frac{qa * Rga + (qlc - 3.41 * Wc) * (Rb + PLFm * Rgm + Rgd * Fsc)}{tg - \frac{twi + two}{2} - tp} \qquad (6)$$

For heating:

$$Lh = \frac{qa * Rga + (qlh - 3.41 * Wh) * (Rb + PLFm * Rgm + Rgd * Fsc)}{tg - \frac{twi + two}{2} - tp} \qquad (7)$$

Table 4. GSHP Loop Length Equation Variables

Variables with an Assumed Probability Distribution					
Abv.	**Parameter**	**Distribution**	**Values**	**Units**	**Ref.**
qlh, qlc	Heating and Cooling Load	Uniform	Location Dependent (Appendix D)	Btu/hr	a,b
tg	Ground Temperature	Uniform	Location Dependent (Appendix D)	°F	a,c,d
PLFm	Part Load Factor	Uniform	Min: 0.18 Max: 0.71	- -	c,e
twi	Temperature of Water Entering the HP	Uniform	Ground temp+25F (± 5F)	°F	c
two	Temperature of Water Exiting the HP	Uniform	Ground temp-12.5F (± 2.5F)	°F	c
Fsc	Number of bores per parallel loop	Bootstrapped	1, 2, or 3 equal probability of occurrence	-	c
Calculated Variables					
Abv.	**Parameter**		**Dependendencies**	**Units**	**Ref.**
qa	Net annual average heat transfer to ground		COP, EER, heat hr, cool hr, qlh, qlc	(Btu/hr)	c
tp	Temperature Penelity		Bore Dist, No. Bores, kg, alpha	°F	c
Rp	Thermal resistance of bore (backfill and pipe)		kbf, kp, U-Tube local, Pipe Diam, Bore Diam	hr-ft-°F/Btu	c
Rga	Effective thermal resistance of the ground annual pulse		kg, gwm (G, Fo, pulse time)	hr-ft-°F/Btu	c
Rgm	Effective thermal resistance of the ground monthly pulse		kg, gwm (G, Fo, pulse time)	hr-ft-°F/Btu	c
Rgd	Effective thermal resistance of the ground daily pulse		kg, gwm (G, Fo, pulse time)	hr-ft-°F/Btu	c
Wc,Wh	Heating and cooling input power		COP, EER, qlh, qlc, n motor, hL, Pipe Diam, mu, rho, Anti%	watts	c

a See Appendix D for minimum and maximum values for each state
b Calculated by Trace 700 software created by Trane Inc.
c ASHRAE Ground-Source Heat Pumps Design of Geothermal Systems (Kavenaugh and Rafferty, 1997)
d ASHRAE Commercial/Institutional Ground-Source Heat Pump Engr Manual (Caneta Research Inc, 1995)
e Part load factor (PLF) is based on operating commercial building operating 5 days per week, and
Min value assumes only one 6 hour block has a heating or cooling load
Max value assumes all four 6 hour blocks have the same heating or cooling load (see ref. e)

Table 4 defines the variables and lists the variable distributions required to calculate the loop length equations. Each variable listed in Equations 6 and 7 are obtained by multiple other relationships, which are based on the variables listed in Table 5. Ground and bore thermal resistance values seen in Equations 6 and 7 (variables annotated by the letter R) are based primarily on the ground's ability to transfer heat, which is based on variables like ground and grout thermal conductivity, thermal diffusivity, groundwater movement, and U-tube pipe spacing within the bore.

Notice that some of the parameters do not have a distribution associated with them. The reason for this is that they are dependent on other values that have been given distributions. Items like pipe diameter, which could have been given a distribution of 3/4 to 1-1/2 inch, are instead calculated based on the selected design values determined from other variables with distributions. Thus, pipe diameter size is calculated based on the selected heating/cooling load, allowable pressure drop range, flow rate per ton, and liquid viscosity/density values. Given these inputs, the spreadsheet model calculates the pipe diameter that will result in an acceptable design velocity (<4 ft/sec) and pressure drop (1 to 4 ft / 100ft of pipe). Likewise, temperature penalty values depend on the selected spacing between bores, borehole diameter is dependent on the pipe diameter selected, bore depth is dependent on pressure drops, etc.

Table 5. Supporting GSHP Loop Length Variables

Variables with an Assumed Probability Distribution					
Abv.	**Parameter**	**Distribution**	**Values**	**Units**	**Ref.**
heat/cool hr	Heating and Cooling Hours	Uniform	Location Dependent (Appendix D)	hr	a,b,c
gpm/ton	Design Liquid Flow Rate per Ton	Uniform	Min: 2 Max: 3	gpm/ton gpm/ton	d
kg	Ground Thermal Conductivity	Uniform	Min: 0.3 Max: 3.6	Btu/(hr-ft-°F) Btu/(hr-ft-°F)	d,e
alpha	Ground Thermal Diffusivity	Uniform	Min: 0.3 Max: 3	ft^2/day ft^2/day	d, e
gwm	Groundwater Movement	Uniform	Min: 10 Max: 1	years years	d, f
kbf	Thermal Conductivity of Backfill/Grout	Uniform	Min: 0.38 Max: 1.5	Btu/(hr-ft-°F) Btu/(hr-ft-°F)	d, g
mu	Viscosity of Antifreeze/Water Mixture	Uniform	Min: 0.0012 Max: 0.004	lb/(ft-s) lb/(ft-s)	h
rho	Density of Antifreeze/Water Mixture	Uniform	Min: 60 Max: 73	lb/ft^3 lb/ft^3	h
u-tube local	U-Tube Location within Bore	Triangular	Min: Tubes touching eachother in borehole Max: Tubes touching outside wall of borehole Most Likely: Tubes evenly spaced in borehole		d, i
n motor	Pump Motor Efficiency	Uniform	Min: 74% Max: 94%	- -	j
hL	U-Tube Head Loss	Uniform	Min: 0.7 Max: 13.7	ft of water ft of water	d, g
Bore Dist	Separation Distance Between Bores	Uniform	Min: 10 Max: 30	ft ft	d
Anti %	Antifreeze Percent by Volume	Uniform	Min: 0 Max: 30	% %	h
Anti $	Antifreeze Cost	Uniform	Min: 4.24 Max: 11.09	$/gal $/gal	h
Calculated Variables					
Abv.	**Parameter**		**Dependendencies**	**Units**	**Ref.**
Pipe D	Pipe Diameter		gpm/ton, hL, mu, rho, Anti%	in	d
Bore D	Borehole Diameter		Pipe Diam	in	
No. Bore	Number of bores		Bore L	-	
Bore L	Bore Depth		Pipe Diam	ft	
Pulse Time	Heat Pulse Time		gwm	hr	
Fo	Fourier Number		Pulse time, gwm, alpha	-	
G	G-Factor		Fo	-	

a	See Appendix D for minimum and maximum values for each state
b	Heating hours developed by Gas Appliance Manufacturers Association (GAMA)
c	Cooling hours developed by Air Conditioning and Refrigeration Institute (ARI)
d	ASHRAE Ground-Source Heat Pumps Design of Geothermal Systems (Kavenaugh and Rafferty, 1997)
e	Based on the min and max thermal conductivity/diffusivity value for all possible soil and rock compositions
f	Ground water movement is based on the number of years required to remove heat stored in the loop field
g	GchpCalc 4.0 software database, http:/www.geokiss.com
h	ASHRAE Commercial/Institutional Ground-Source Heat Pump Engr Manual (Caneta Research Inc, 1995)
i	Remund and Paul, 1997 (EPRI Report No. TR-109169)
j	Energy Policy Act of 1992 (EPACT)

To ensure confidence in the Monte Carlo simulation, the resulting loop lengths were compared to the output produced by the Vertical Ground-Coupled

Heat Pump GchpCalc Version 4.0 software program created by the University of Alabama. Using the same discreet numeric input values for both models, the total loop length results were within ±10% of each other for 15 different scenarios evaluated. This slight variation is a result of the different empirical data used to compute the G-factor, which is one of the variables used to compute the thermal resistance of the ground. Using the Monte Carlo simulation, the input variables are distributions rather than discreet single numbers; thus, the Monte Carlo simulation captures the variability in loop lengths.

HVAC System Start-up Cost

The installation (start-up) cost for each HVAC system can now be evaluated for each state based on the required HVAC equipment size (heating and cooling load) and GSHP total loop length distributions. Start-up cost values are obtained from the RS Means Facilities Construction Cost Data 2001 Unit Price Book (UPB), which is used by contractors, government agencies and facilities professionals throughout the U.S. for estimating construction project cost. The UPB contains national cost averages for labor, equipment, and materials for over 40,000 items necessary for almost any construction or repair project. Only the labor and material cost associated with the specified HVAC units will be considered. Items like interconnecting tubing, valves, curbs, and pads will not be considered as these costs are site specific and relatively minor in comparison to the unit cost. The GSHP will include the additional cost of the grout backfill, drilling, piping, and the heat pump unit. These costs are dependent on the design values chosen within the distributions of the Monte

Carlo simulation. For example, given a selected grout thermal conductivity, the ratio and number of bags of bentonite and silica sand required to achieve this value are computed and priced accordingly. Appendix E and F contain the UPB cost line items used in this study.

To reflect local economics, the UPB also contains city cost index coefficients that are multiplied by the base cost listed in the UPB. In this study, state cost indexes were developed by selecting the minimum and maximum city cost index within each state (see Appendix G). The UPB cost is also multiplied by a randomly selected value within ± 10% to account for additional uncertainty. While the city cost index accounts for local labor, equipment, and material cost, it does not account for the physical properties of the local ground conditions. The local ground condition will add additional variability to the single average $7.55 per foot of drilling listed in the UPB. This variability is due to the uncertainty surrounding the ease or difficulty of drilling a vertical bore hole for the geothermal ground loop at each location. Because of this uncertainty, the UPB drilling price is multiplied by a randomly selected value within ± 50%.

Annual Operating Cost

Solving for annual operating cost for each HVAC system requires distribution estimates for utility rates. Utility price distributions for electricity, natural gas, No. 2 distillate heating fuel oil, and liquid petroleum gas (LPG), are obtained from the U.S. Government DOE Energy Information Administration's (EIA) database. This database contains monthly electrical and natural gas prices for each state; however, heating fuel oil and liquid petroleum gas prices

are categorized by districts rather than by state. From Figure 16, it can be seen that there are five districts in the U.S.; note that district I is further divided into sub-districts IA, IB, and IC. Utility prices for each state's fuel oil and liquid petroleum gas are thus represented by the district (or sub-districts) it reside in.

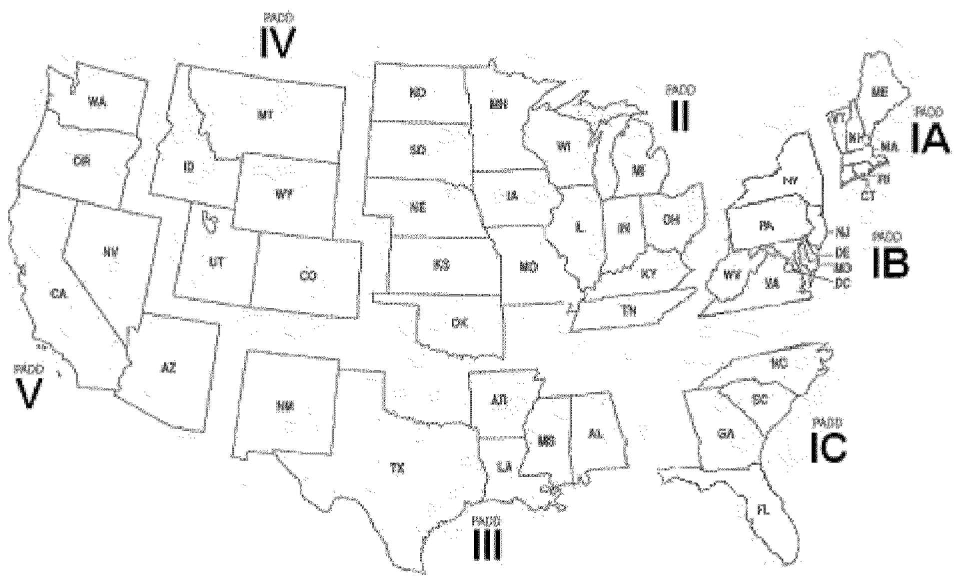


Figure 16. Districts for heating fuel oil and liquid petroleum gas sales

The electric, natural gas, fuel oil, and LPG utility rate probability distributions will initially consist of triangular distributions including the minimum, maximum and average monthly utility rate at each state for the year 2000 (see Table 6 for these values). However, in the year 2000 the U.S. witnessed utility prices that, on a national average, were higher than those of previous years. To encompass the additional variability and uncertainty associated with a different baseline evaluation year, the Annual Energy Outlook 2002 (AEO 2002) projections for year 2020 were also used. Table 7 displays the commercial 2020 low and high estimated percent change from year 2000 utility prices.

Table 6. Initial State Commercial Utility Rate Distributions for 2000 (DOE, 2000)

State	Electricity (cents/kWh)			Natural Gas ($/MCF)			Fuel Oil ($/Gal)			LPG ($/Gal)		
	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
Alabama	6.2	7.1	6.6	6.43	9.40	7.97	0.784	1.033	0.899	0.927	1.248	1.031
Arizona	6.7	8.1	7.3	5.93	7.88	6.70	0.865	1.260	1.029	1.046	1.458	1.138
Arkansas	5.5	6.2	5.9	3.24	8.56	5.73	0.784	1.033	0.899	0.927	1.248	1.031
California	8.1	10.6	9.2	6.20	10.41	7.51	0.865	1.260	1.029	1.046	1.458	1.138
Colorado	5.1	6.4	5.6	4.74	6.37	5.47	0.777	1.146	0.958	0.886	1.249	1.033
Connecticut	8.5	9.6	9.3	3.97	8.38	6.23	0.890	1.140	1.020	0.983	1.212	1.083
Delaware	5.0	7.2	6.5	5.73	18.75	8.03	0.859	1.110	0.985	1.001	1.251	1.091
Florida	5.9	6.5	6.2	6.78	9.19	7.77	0.861	1.103	0.965	0.976	1.252	1.069
Georgia	6.1	6.9	6.6	2.45	9.67	7.72	0.861	1.103	0.965	0.976	1.252	1.069
Idaho	4.0	4.4	4.3	4.79	6.60	5.61	0.777	1.460	0.958	0.886	1.249	1.033
Illinois	6.1	8.0	7.1	4.92	10.33	7.83	0.778	1.069	0.930	0.818	1.157	0.954
Indiana	5.6	6.1	5.9	4.81	7.00	6.02	0.778	1.069	0.930	0.818	1.157	0.954
Iowa	6.2	7.3	6.6	4.62	9.70	7.34	0.778	1.069	0.930	0.818	1.157	0.954
Kansas	5.7	6.7	6.2	5.55	8.69	7.19	0.778	1.069	0.930	0.818	1.157	0.954
Kentucky	4.7	5.2	5.1	5.35	8.43	6.90	0.778	1.069	0.930	0.818	1.157	0.954
Louisiana	6.5	8.5	7.3	5.19	10.95	7.52	0.784	1.033	0.899	0.927	1.248	1.031
Maine	9.2	11.5	10.7	1.76	9.95	6.93	0.890	1.140	1.020	0.983	1.212	1.083
Maryland	5.3	8.2	6.5	6.49	10.92	8.65	0.859	1.110	0.985	1.001	1.215	1.091
Massachusetts	7.5	10.7	9.0	6.70	10.53	8.43	0.890	1.140	1.020	0.983	1.212	1.083
Michigan	7.7	8.2	7.9	4.59	5.93	5.08	0.778	1.069	0.930	0.818	1.157	0.954
Minnesota	5.8	6.8	6.2	4.63	8.13	6.03	0.778	1.069	0.930	0.818	1.157	0.954
Mississippi	6.4	6.8	6.5	5.19	8.96	6.64	0.784	1.033	0.899	0.927	1.248	1.031
Missouri	4.6	7.2	5.8	5.56	9.00	7.17	0.778	1.069	0.930	0.818	1.157	0.954
Montana	5.0	6.8	5.9	5.19	7.82	6.26	0.777	1.146	0.958	0.886	1.249	1.033
Nebraska	4.9	6.4	5.4	4.19	7.44	5.63	0.778	1.069	0.930	0.818	1.157	0.954
Nevada	6.3	7.3	6.7	5.37	5.87	5.61	0.865	1.260	1.029	1.046	1.458	1.138
New Hampshire	10.7	11.7	11.3	6.84	10.78	8.55	0.890	1.140	1.020	0.983	1.212	1.083
New Jersey	7.9	9.2	8.6	1.94	9.43	5.82	0.859	1.110	0.985	1.001	1.251	1.091
New Mexico	6.5	7.4	7.0	3.66	7.77	5.01	0.784	1.033	0.899	0.927	1.248	1.031
New York	10.3	15.0	12.2	4.80	12.11	7.58	0.859	1.110	0.985	1.001	1.251	1.091
North Carolina	6.2	6.6	6.4	6.26	9.39	7.72	0.861	1.103	0.965	0.976	1.252	1.069
North Dakota	5.5	6.2	6.0	4.36	7.67	6.07	0.778	1.069	0.930	0.818	1.157	0.954
Ohio	7.2	7.9	7.6	5.83	8.94	7.40	0.778	1.069	0.930	0.818	1.157	0.954
Oklahoma	4.7	7.3	6.1	5.38	7.75	6.63	0.778	1.069	0.930	0.818	1.157	0.954
Oregon	5.0	5.2	5.1	5.32	10.23	6.11	0.865	1.260	1.029	1.046	1.458	1.138
Pennsylvania	5.7	7.2	6.3	6.77	8.99	7.92	0.859	1.110	0.985	1.001	1.251	1.091
Rhode Island	7.5	12.2	9.8	7.13	10.72	9.07	0.890	1.140	1.020	0.983	1.212	1.083
South Carolina	5.8	6.4	6.1	6.45	9.62	7.63	0.861	1.103	0.965	0.976	1.252	1.069
South Dakota	6.3	6.8	6.6	4.36	7.96	6.43	0.778	1.069	0.930	0.818	1.157	0.954
Tennessee	5.8	6.7	6.3	4.94	8.65	7.13	0.778	1.069	0.930	0.818	1.157	0.954
Texas	6.5	7.5	6.8	4.54	7.39	5.81	0.784	1.033	0.899	0.927	1.248	1.031
Utah	4.9	5.5	5.2	4.26	5.46	4.76	0.777	1.146	0.958	0.886	1.249	1.033
Vermont	9.3	12.4	10.6	6.17	7.72	6.48	0.890	1.140	1.020	0.983	1.212	1.083
Virginia	5.4	5.9	5.7	6.13	9.82	7.67	0.859	1.110	0.985	1.001	1.251	1.091
Washington	4.6	5.2	4.9	5.32	7.11	6.07	0.865	1.260	1.029	1.046	1.458	1.138
West Virginia	5.3	5.7	5.5	6.23	7.35	6.78	0.859	1.110	0.985	1.001	1.251	1.091
Wisconsin	5.7	6.4	6.0	5.03	8.34	6.29	0.778	1.069	0.930	0.818	1.157	0.954
Wyoming	5.1	5.5	5.3	3.81	7.48	5.27	0.777	1.146	0.958	0.886	1.249	1.033

Table 7. Projected Commercial Utility Price Percent Change from 2000 to 2020.

Utility Type	Low	High
Electricity	-12.3%	-3.2%
Natural Gas	-10.6%	-0.3%
No.2 Distillate Fuel Oil	-30.2%	6.9%
Petroleum (LPG)	-23.6%	12.0%
Source: (DOE, 2002)		

The AEO 2002 projections for year 2020 were evaluated by the EIA under assumptions of low and high economic growth and low and high world oil price scenarios. For this study, the Monte Carlo simulation selects an initial utility rate (for each state or district) from within the year 2000 triangular distribution (Table 6). This value is then multiplied by the low and high percent change to form a new uniform distribution. The Monte Carlo simulation then randomly selects a utility price from within this new distribution. This process is repeated 10,000

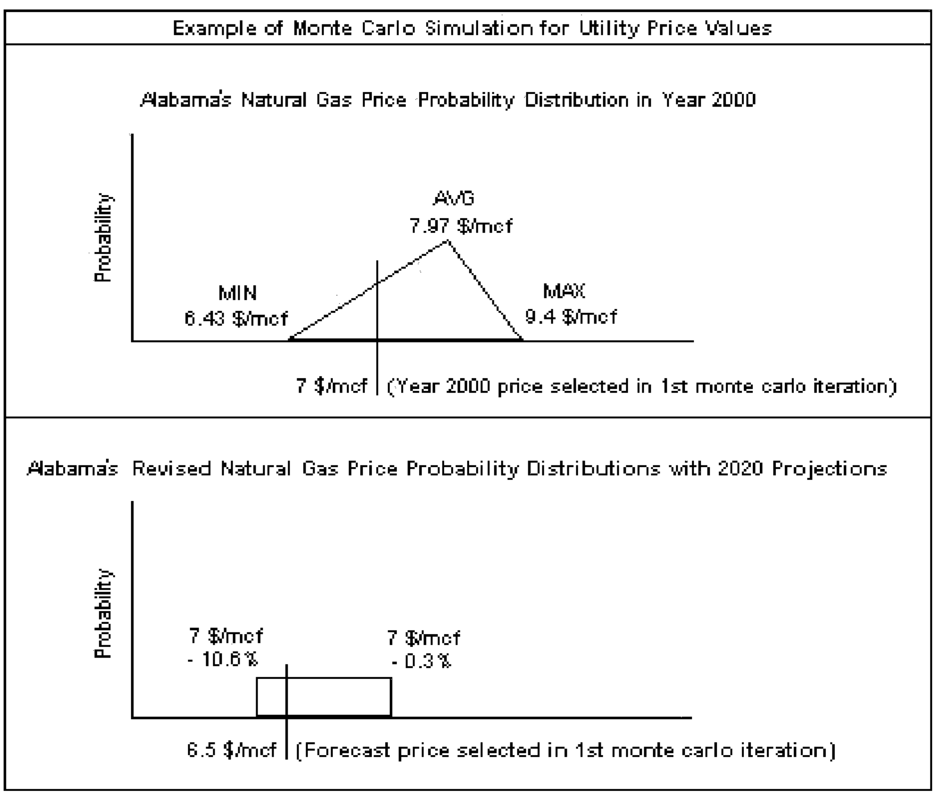


Figure 17. Example of Monte Carlo Simulation for Utility Price Values

times for each state. Figure 17 is a graphical illustration of this process for a single Monte Carlo iteration for the natural gas price in Alabama.

The annual operating cost is computed by Equation 9. Utility rates for natural gas, fuel heating oil, and liquid petroleum gas are expressed in units of dollars per thousand cubic feet ($/MCF) and dollars per gallon ($/Gal), respectively. These rates are converted to units of dollars per watt-hour ($/Whr) by using the energy density conversion factors (which are also probability distributions) seen in Table 8.

$$AOC = AEC * UR \qquad (9)$$

where

AOC = Annual Operating Cost ($/yr)
AEC = Annual Energy Consumption (Watt-hr/yr)
UR = Utility Rate ($/Watt-hr)

Table 8. Distributions for Fossil Fuel Energy Content

	Parameter	Distribution	Values	Ref.
1	Natural Gas Energy Content	Single Point	1,000,000 Btu/MCF	a,b,c
2	Fuel Heating Oil Energy Content	Uniform	Min: 138,000 Btu/gal Max: 140,000 Btu/gal	c b
3	Liquid Petroleum Gas Energy Content	Uniform	Min: 90.000 Btu/gal Max: 91,600 Btu/gal	c b
Source: (a. GAMA, 2001), (b. DOE, 2000), (c. Geo-Heat, 2001)				

Life Cycle Cost Analysis

In January of 2000, the U.S. federal government established FEMP under Title 10 of the Code of Federal Regulations (10 CFR 436). This code requires that decisions of funding for federal project be based on Life Cycle Cost (LCC) Analyses. The LCC portion of the model will compute the labor and material cost associated with the start-up (installed) and annual operating cost for each HVAC

system. The analysis is based on a 50-year evaluation period. The expected life distributions for each HVAC system are listed in Table 9. Units may require replacement anywhere from one to four times during the specified evaluation period. It is important to note that the geothermal ground loop heat exchanger is assumed to be a one-time cost. When the ground source heat pump system requires replacement, only the heat pump cost is added. Most manufacturers of ground loop heat exchangers offer a 50-year warranty. A report published by Plastics Pipe Institute indicates that the high-density polyethylene pipe used in the closed loop system has a mean projected failure time of 165 years (Plastic Pipe Institute, 1999).

Table 9. Distributions for HVAC Unit Life Expectancy

Systems	Distribution	Values
GSHP (heat pump only)	Uniform	Min: 12 years Max: 20 years
ASHP	Uniform	Min: 12 years Max: 20 years
AC	Uniform	Min: 12 years Max: 20 years
Furnace	Uniform	Min: 12 years Max: 25 years
Electrical Resistance Heater	Uniform	Min: 12 years Max: 25 years
Source: (Interlaboratory Working Group, 2000)		

Equation 8 is used to assess life cycle cost.

$$LCC = SC * \frac{EP}{EL} + AOC * EP \qquad (8)$$

where

LCC = Life Cycle Cost ($/50 years)
SC = Start-up Cost ($)
EP = Evaluation Period (50 years)
EL = Expected Life of HVAC System (yr)
AOC = Annual Operating Cost ($/yr)

Payback Analysis

The payback period is a measure of the amount of time to recover the higher start-up cost of the GSHP (relative to other conventional systems) divided by the annual savings provided by the GSHP. The larger the savings in annual operating cost, the quicker the payback. Equation 10 is the simple payback equation used for this study. Payback periods are perhaps the best way to view the results as it encompasses all of the input distributions, i.e., energy consumption, start-up, and operating cost, for both the GSHP and the conventional HVAC system to which it is compared. The DoD requires energy projects that have a 10-year or less payback to be eligible for funding (A-GRAM 99-22, 1999).

$$PBP = \frac{\Delta SC}{\Delta AOC} \tag{10}$$

where

PBP = Payback Period (years)
ΔSC = Difference in Start-up Cost ($)
ΔAOC = Difference in Annual Operating Cost ($/yr)

IV. Results

Monte Carlo Simulation Output Overview

Results of the Monte Carlo simulation are based on the probability output distributions obtained from the Crystal Ball spreadsheet model. The output distributions are then presented as box-and-whisker plots so that multiple comparisons between HVAC systems can be more easily displayed. Figure 18 is an example of the output probability distribution (along with its box-and-whisker plot) for the loop length required in the 2,000 square foot (s.f.) office building located in Texas. Notice that the median loop length required is 1,356 ft; however, it could be much shorter or longer depending on the input variables selected in the simulation.

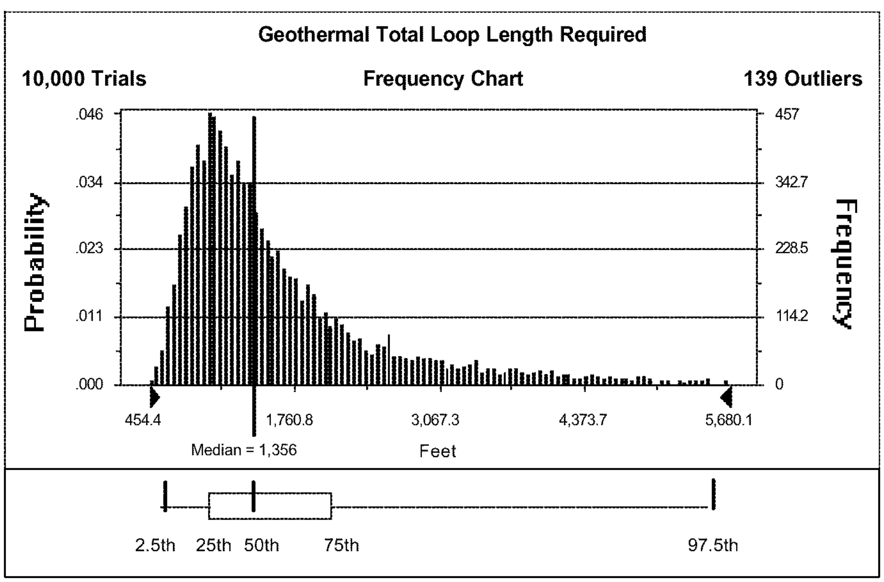


Figure 18. Total loop length probability distribution for Texas

According to Figure 18, 97.5% of the time the required loop length will be less than 4,916 ft; 75% of the time the length will be less than 1,985 ft; 50% of the time it will be less than 1,356 ft; and so on. The "whiskers" represent the 2.5th and 97.5th percentile. The ends of the box are the observed values at the 25th and 75th percentile, and the line within the box is the 50th percentile.

To illustrate the model outputs, the following four states were selected for detailed evaluation: Idaho, California, South Carolina, and Texas. These four states were selected based on their payback periods. Idaho represents a state with one of the shortest payback period distributions, California had the longest expected payback period distribution, and South Carolina and Texas have average payback periods relative to all other states. Tabular results for each state (excluding Hawaii and Alaska) are located in Appendices H through K.

Annual Energy Consumption (AEC) Results

The 50th percentile for annual energy consumption of GSHPs is lower than all other conventional HVAC systems for the 48 U.S. states evaluated. The average 50th percentile values for GSHP annual energy consumption in the U.S. was 33% lower than ASHP, 68% lower than Air-Cooled air conditioning with Natural Gas furnace (AC/NG), 69% lower than Air-Cooled air conditioning with heating fuel Oil furnace (AC/Oil), 68% lower than Air-Cooled air conditioning with Liquid Petroleum Gas furnace (AC/LPG), and 63% lower than Air-Cooled air conditioning with Electrical resistance coil (AC/Elec). The annual energy consumption for each HVAC system at the four selected states is shown in Figure 19. The GSHP generally consumes less energy than the conventional

systems; however, the ASHP in California and Texas overlap the GSHPs to some degree.

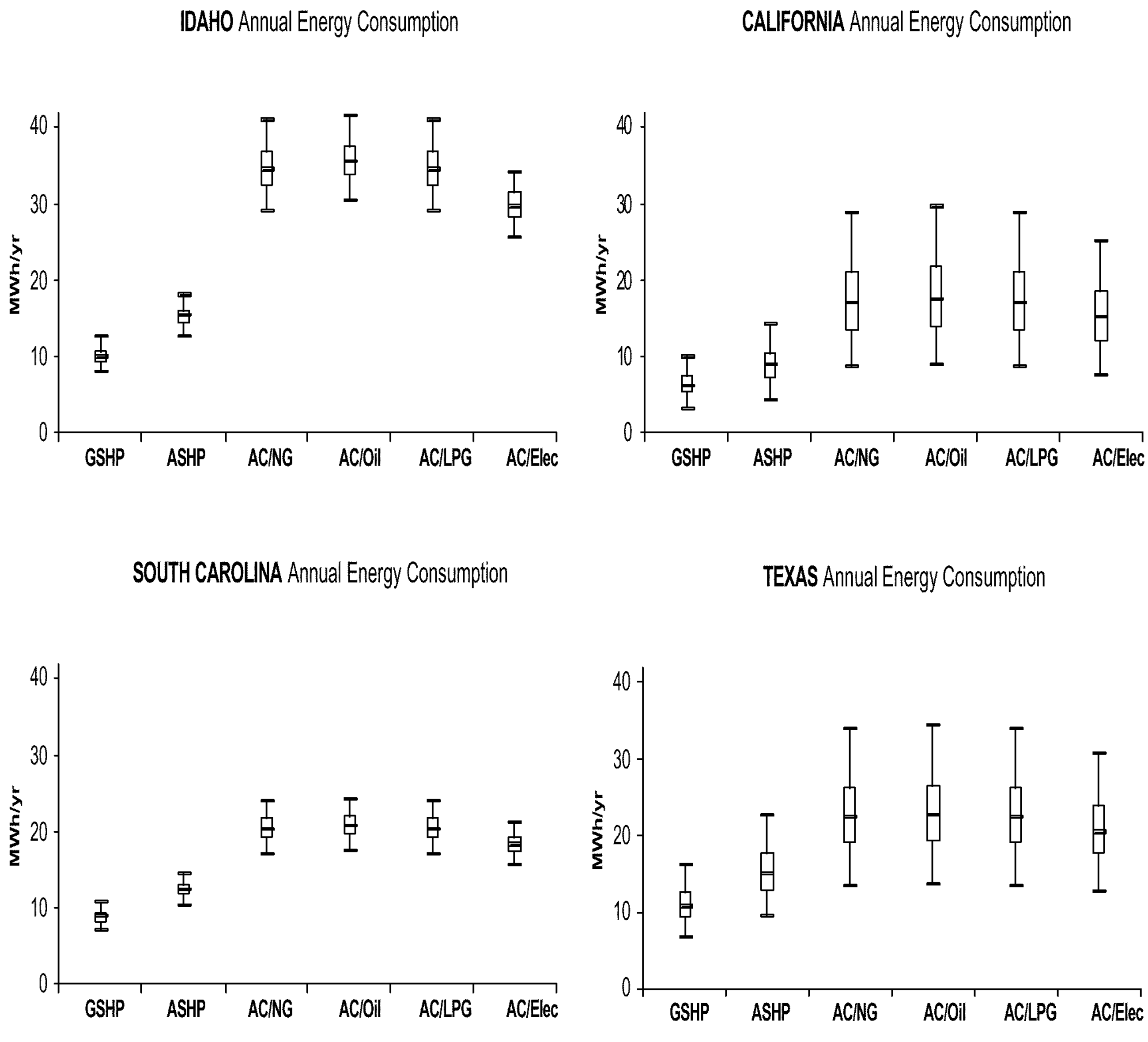


Figure 19. Commercial HVAC Annual Energy Consumption for ID, CA, SC, and TX

A sensitivity analysis was performed to determine which input variable distributions had the greatest contribution to variance (influence) on GSHP annual energy consumption for each state. The input variable's contribution to variance affects the outcome in one of two ways: the variable has a wide range of possible values and thus contributes to a wider range of possible outcomes, or the variable has little variance but has a strong mathematical relation to the outcome so a slight change in its variance will greatly affect the outcome. Table 10 depicts each state's input variables that influence GSHP annual energy consumption by more than 5%; the variable that contributes the most variability for each state's outcome is highlighted.

It is evident that the annual energy consumed is sensitive to different input parameters for each state; however, the GSHP heating COP is one of the most influential variables to GSHP annual energy consumption. In states like Texas and South Carolina, where cooling needs are high, the COP becomes less important and the cooling EER and annual cooling hours become more influential. Also, because Texas covers more surface area than South Carolina, Texas has a wider distribution of possible annual cooling hours, which causes cooling hours to become more influential than EER when computing the annual energy consumption.

Table 10. Sensitivity Analysis for GSHP Annual Energy Consumption

State	GSHP Annual Energy Consumption (AEC)					
	GSHP COP	Heating Load	Cooling Load	Annual Heating Hr	Annual Cooling Hr	GSHP EER
AL	8.7%		10.6%	7.2%	36.3%	31.4%
AZ	20.4%		23.9%	8.7%	19.6%	18.8%
AR	26.6%	5.2%	14.7%		6.3%	41.8%
CA	5.5%	42.7%		13.6%	33.8%	
CO		40.6%		15.5%	34.7%	
CT	46.1%	33.5%		12.4%		
DE	52.3%	14.0%	16.4%			11.0%
FL			21.2%		27.4%	45.8%
GA	12.6%		14.3%	10.4%	33.5%	22.8%
ID	59.4%	14.8%		18.4%		
IL	29.6%	47.5%	9.6%		6.3%	
IN	58.8%	20.1%	5.2%			7.2%
IA	43.3%	46.7%				
KS	30.1%	42.3%	7.0%	12.6%		
KY	40.6%	14.1%	10.5%	17.9%		11.5%
LA			16.0%		38.4%	39.0%
ME	66.4%	24.5%		5.2%		
MD	60.5%	15.4%	5.2%			12.0%
MA	63.0%	17.1%		17.2%		
MI	54.5%	29.0%			9.3%	
MN	57.0%	27.4%		10.0%		
MS	8.2%		11.2%	6.3%	37.1%	32.1%
MO	42.3%	9.2%	8.5%	16.9%		19.5%
MT	58.8%	21.5%		15.0%		
NE	66.4%	17.1%				6.2%
NV	24.2%	17.6%	21.0%		25.7%	8.8%
NH	73.6%	17.4%		5.8%		
NJ	67.5%	16.3%				5.1%
NM	35.5%	8.0%		14.9%	27.7%	8.4%
NY	42.1%	41.1%		10.4%		
NC	37.5%	8.7%	11.2%		6.2%	30.3%
ND	70.2%	21.9%				
OH	64.6%	15.8%		5.4%		6.3%
OK	36.4%	8.1%	11.1%		7.0%	31.1%
OR	41.5%	9.9%	7.7%	38.9%		
PA	46.8%	38.0%	6.1%			
RI	72.8%	17.5%				
SC	19.3%		12.0%	16.1%	8.9%	36.5%
SD	59.5%	17.4%		16.7%		
TN	24.7%	14.3%	25.2%		6.0%	24.5%
TX		10.8%	15.7%	9.6%	51.9%	9.0%
UT	68.2%	17.1%				
VT	72.8%	19.1%				
VA	42.8%	17.9%	7.6%	18.0%		10.1%
WA	17.2%	62.7%		16.6%		
WV	61.6%	14.6%				11.8%
WI	50.9%	37.9%		8.8%		
WY	63.7%	17.0%		16.8%		
USA	45.8%	22.4%		11.3%	6.6%	6.4%

Annual Operating Cost (AOC) Results

The 50th percentile for annual operating cost of GSHP is lower than all other conventional HVAC systems for 42 of the 48 states evaluated. The average 50th percentile for GSHP annual operating cost in the U.S. was:

- 33% lower than ASHP
- 25% lower than AC/NG
- 27% lower than AC/Oil
- 49% lower than AC/LPG
- 63% lower than AC/Elec

The six states that had conventional HVAC systems with 50th percentile annual operating costs lower than that of the GSHP were: Connecticut, Maine, Michigan, New Hampshire, New York, and Vermont. In these states, the difference between the 50th percentiles of GSHP compared to the AC/NG and AC/Oil systems was from 1% to 14% above the annual operating cost of the GSHP. These six states have a higher probability of a lower operating cost because they have both a higher electricity costs and lower natural gas and fuel oil cost than most other states. The annual operating cost for each commercial HVAC system at the four selected states is shown in Figure 20.

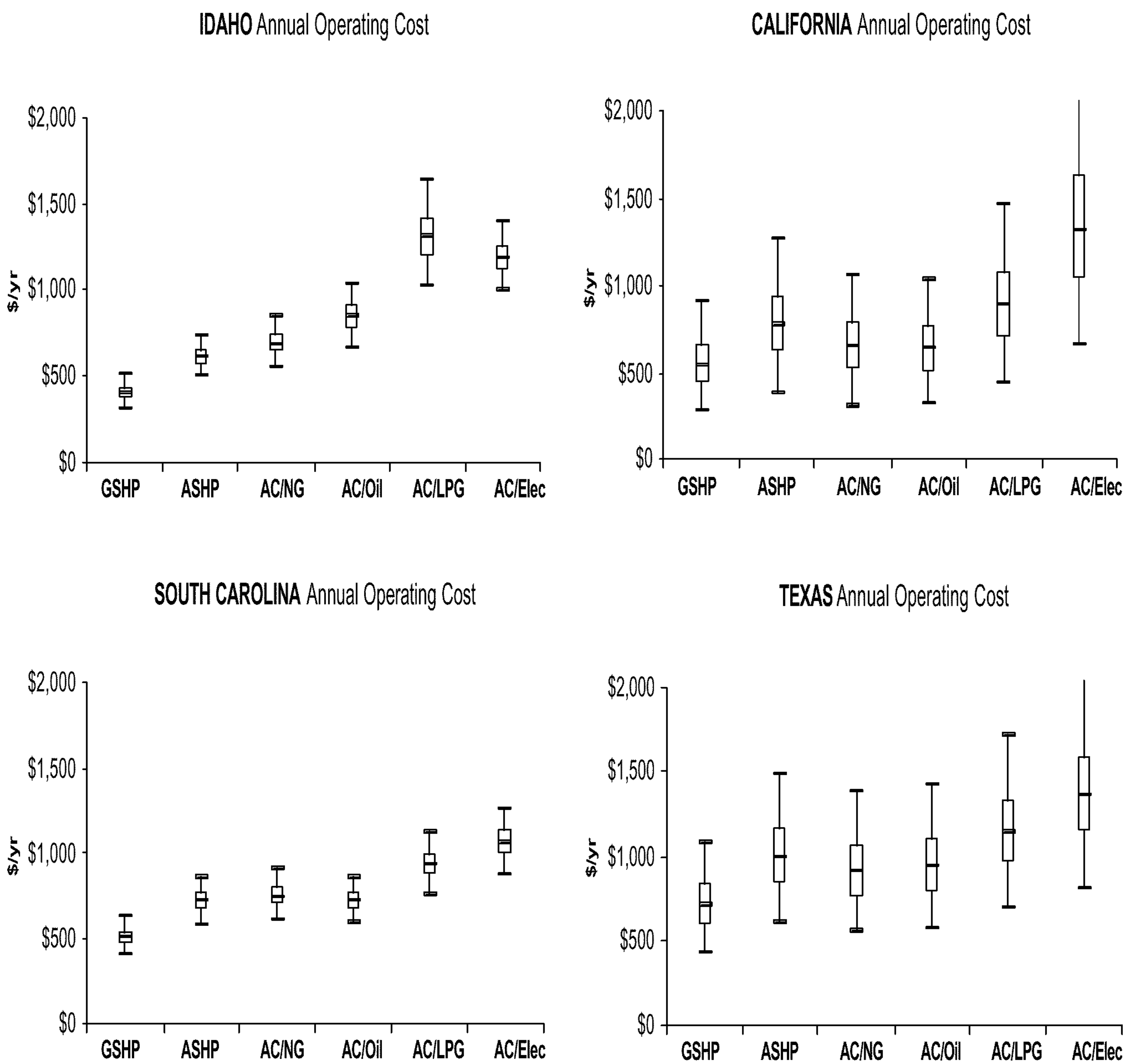


Figure 20. Commercial HVAC Annual Operating Cost for ID, CA, SC, and TX

The sensitivity analysis for the annual operating cost of each state is displayed in Table 11. This analysis shows once again the COP value selected is normally one of the most influential variables to annual operating cost. For warm weather states that require more cooling; the EER, annual cooling hours, and cooling loads become more influential. The price of electricity is the most influential variable in states like Delaware, Maryland, Missouri, New York, Oklahoma, and Rhode Island where electricity prices have more variance and are either higher or lower than the national average. The sensitivity analysis is a measure of a variable's contribution to variance; thus, in states like Idaho, which have a relatively narrow range of variance in the prices of electricity, there is not a great deal of influence from electricity prices. However, the fact that Idaho has the lowest electricity prices in the nation is important when comparing the annual operating cost between states.

Table 11. Sensitivity Analysis for GSHP Annual Operating Cost

State	GSHP Annual Operating Cost (AOC)						
	GSHP COP	Electric Price	GSHP EER	Heat Load	Cooling Load	Annual Heating Hr	Annual Cooling Hr
AL	7.0%	14.6%	26.8%		9.1%		31.1%
AZ	15.8%	18.7%	15.8%		19.3%		15.7%
AR	21.0%	20.5%	33.1%		12.4%		
CA				38.5%		14.4%	33.7%
CO	50.9%	24.4%		6.0%		14.1%	
CT	41.7%	11.8%		29.3%		11.1%	
DE	27.4%	46.1%	6.6%	7.1%	8.9%		
FL		7.7%	42.6%		19.4%		25.2%
GA	11.5%	12.2%	19.5%		12.8%		29.1%
ID	51.9%	11.9%		13.3%		16.2%	
IL	24.8%	18.6%		38.5%	7.8%		
IN	52.1%	12.8%	5.9%	17.5%			
IA	37.0%	14.0%		40.2%			
KS	26.5%	11.8%		37.0%	6.3%	11.3%	
KY	34.3%	14.6%		12.2%	9.7%	15.2%	
LA		24.1%	30.0%		11.9%		28.5%
ME	51.6%	20.0%		20.4%			
MD	24.7%	58.9%		6.0%			
MA	40.6%	34.9%		10.9%		11.7%	
MI	51.5%	6.2%		27.3%		8.5%	
MN	50.2%	12.3%		23.8%		8.7%	
MS	7.7%	6.7%	29.9%		10.3%		34.5%
MO	19.9%	53.4%	8.7%			8.7%	
MT	42.6%	27.6%		14.8%		11.4%	
NE	44.3%	33.5%		9.9%			
NV	21.1%	13.7%		15.2%	18.2%		21.4%
NH	65.2%	10.9%		15.6%		5.3%	
NJ	53.5%	19.9%		13.0%			
NM	31.0%	12.4%		7.6%		13.2%	23.7%
NY	29.4%	29.5%		28.3%		8.0%	
NC	32.2%	12.2%	26.4%	7.9%	10.3%		
ND	61.6%	12.4%		19.1%			
OH	54.7%	14.0%	5.5%	13.8%			
OK	15.9%	57.9%	12.2%				
OR	40.6%			9.4%		37.8%	7.3%
PA	36.6%	21.0%		30.4%			
RI	35.5%	52.0%		8.3%			
SC	16.1%	15.5%	30.9%		10.3%	13.3%	
SD	53.6%	9.0%		15.4%			15.8%
TN	19.4%	19.4%	20.5%	10.8%	20.2%		
TX			8.7%	10.2%	15.2%	9.4%	49.7%
UT	58.1%	14.8%		14.5%			
VT	50.3%	30.0%		13.6%			
VA	37.4%	12.5%	9.0%	15.8%		15.1%	
WA	16.5%			60.4%		15.5%	
WV	52.7%	12.9%	10.1%	13.0%			
WI	46.5%	9.2%		33.8%		8.1%	
WY	58.1%	8.4%		15.4%		16.1%	
USA	36.3%	20.7%		17.7%		9.1%	5.3%

Life Cycle Cost (LCC) Results

Life cycle cost is measured over a 50-year evaluation period and takes into account the life expectancy probability distributions of each HVAC system. The 50th percentile for total life cycle cost of GSHPs is lower than all other conventional HVAC systems for 41 of the 48 states evaluated. The average 50th percentile for GSHP life cycle cost in the U.S. was:

- 23% lower than ASHP
- 16% lower than AC/NG
- 18% lower than AC/Oil
- 39% lower than AC/LPG
- 53% lower than AC/Elec.

The seven states where air-cooled AC with natural gas or oil furnace systems had a lower 50th percentile life cycle cost are: Connecticut, Main, Michigan, New Hampshire, New Jersey, New York, and Vermont. For those seven states, the difference between the 50th percentiles of GSHPs and AC/NG and AC/Oil systems ranged from 1% to 15% above the LCC of GSHPs. The life cycle cost for each HVAC system at the four selected states is shown in Figure 21. The sensitivity report for the life cycle cost of the GSHP is shown in Table 12. The sensitivity analysis results are very similar to that of the annual operating cost, but now the variance in the output data also accounts for the variance in life expectancy and start-up cost of all HVAC systems.

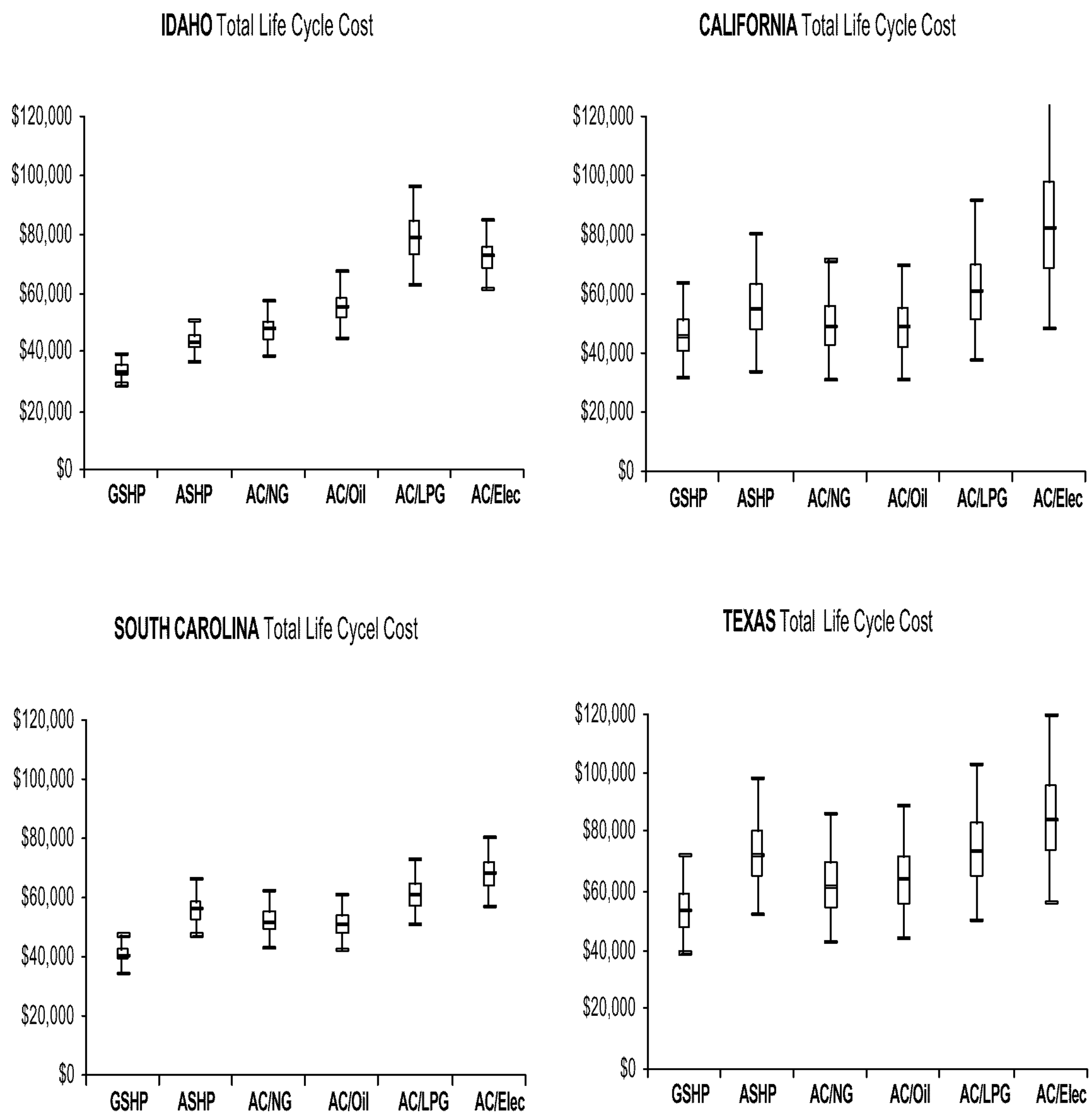


Figure 21. Commercial HVAC Life Cycle Cost for ID, CA, SC, and TX over 50 Years

Table 12. Sensitivity Analysis for GSHP Life Cycle Cost

State	GSHP Life Cycle Cost (LCC)							
	GSHP COP	Electric Price	GSHP EER	Heat Load	Cooling Load	Annual Heating Hr	Annual Cooling Hr	GSHP Exp Life
AL		12.9%	21.9%		7.8%		25.9%	10.3%
AZ	14.4%	16.1%	14.4%		16.7%		13.2%	
AR	16.7%	14.5%	25.5%		10.0%			15.4%
CA				36.5%		14.1%	31.6%	
CO	43.7%	21.5%		5.1%		12.7%		7.9%
CT	38.5%	11.8%		27.2%		10.4%		
DE	22.9%	40.6%		6.5%	7.5%			9.1%
FL		7.1%	36.7%		16.9%		22.3%	7.4%
GA	10.1%	10.6%	17.7%		10.9%		25.8%	
ID	40.3%	9.6%		9.9%		12.7%		16.1%
IL	23.3%	17.0%		34.8%	7.3%			5.5%
IN	40.2%	11.0%		13.8%				11.7%
IA	35.1%	13.3%		37.5%				
KS	24.1%	11.2%		33.7%	5.8%	10.3%		
KY	28.1%	11.2%		9.3%		10.7%		15.1%
LA		21.9%	26.3%		10.9%		25.4%	6.6%
ME	50.5%	19.5%		20.0%				
MD	22.6%	52.3%		6.0%				6.1%
MA	38.4%	33.7%		10.0%		11.2%		
MI	50.0%	6.0%		26.0%		8.1%		
MN	45.7%	11.4%		29.1%		7.4%		
MS	6.8%		26.3%		9.0%		29.1%	8.8%
MO	16.6%	43.8%	6.9%			7.3%		10.7%
MT	39.1%	24.9%		13.0%		10.3%		5.4%
NE	39.0%	29.5%		8.7%				8.3%
NV	18.2%	11.7%		13.6%	14.5%		18.1%	
NH	63.8%	10.7%		15.1%		5.5%		
NJ	46.3%	17.0%		10.6%				7.9%
NM	27.5%	11.4%		7.0%		12.0%	20.6%	
NY	29.1%	29.0%		27.5%		8.0%		
NC	26.0%	9.8%	22.8%		8.6%			12.6%
ND	55.9%	11.3%		17.7%				5.1%
OH	48.8%	12.2%	5.1%	12.2%				6.8%
OK	14.2%	50.0%	10.9%					8.8%
OR	33.8%			8.0%		32.0%	6.2%	9.6%
PA	31.3%	18.3%		26.8%				7.5%
RI	33.7%	49.1%		8.0%				
SC	13.0%	11.8%	23.7%			10.7%		14.6%
SD	49.7%	8.5%		14.6%		14.7%		
TN	15.5%	15.2%	17.1%		16.0%			13.5%
TX			8.5%	10.0%	14.5%	9.1%	48.0%	
UT	48.5%	12.9%		12.2%				10.6%
VT	49.4%	29.3%		13.4%				
VA	30.8%	10.1%		12.3%		12.5%		11.2%
WA	15.4%			56.7%		14.8%		
WV	37.4%	9.1%	8.1%	9.6%				18.1%
WI	43.4%	8.5%		31.4%		7.2%		
WY	52.8%	7.6%		13.3%		15.2%		5.5%
USA	32.2%	18.4%		15.7%		8.2%		7.5%

Payback Period Results

The average 50th percentile for GSHP payback period in the U.S. was 7.5 years compared against the ASHP, 9.2 years for AC/NG, 7.9 years for AC/Oil, 3.1 years for AC/LPG, and 1.8 years for AC/Elec. The payback period for each commercial HVAC system at the four selected states is shown in Figure 22. The distributions associated with payback periods have a great deal of variance (long box-and-whiskers) because the payback period accounts for every input variable distribution of both the GSHP and the HVAC system it is compared with.

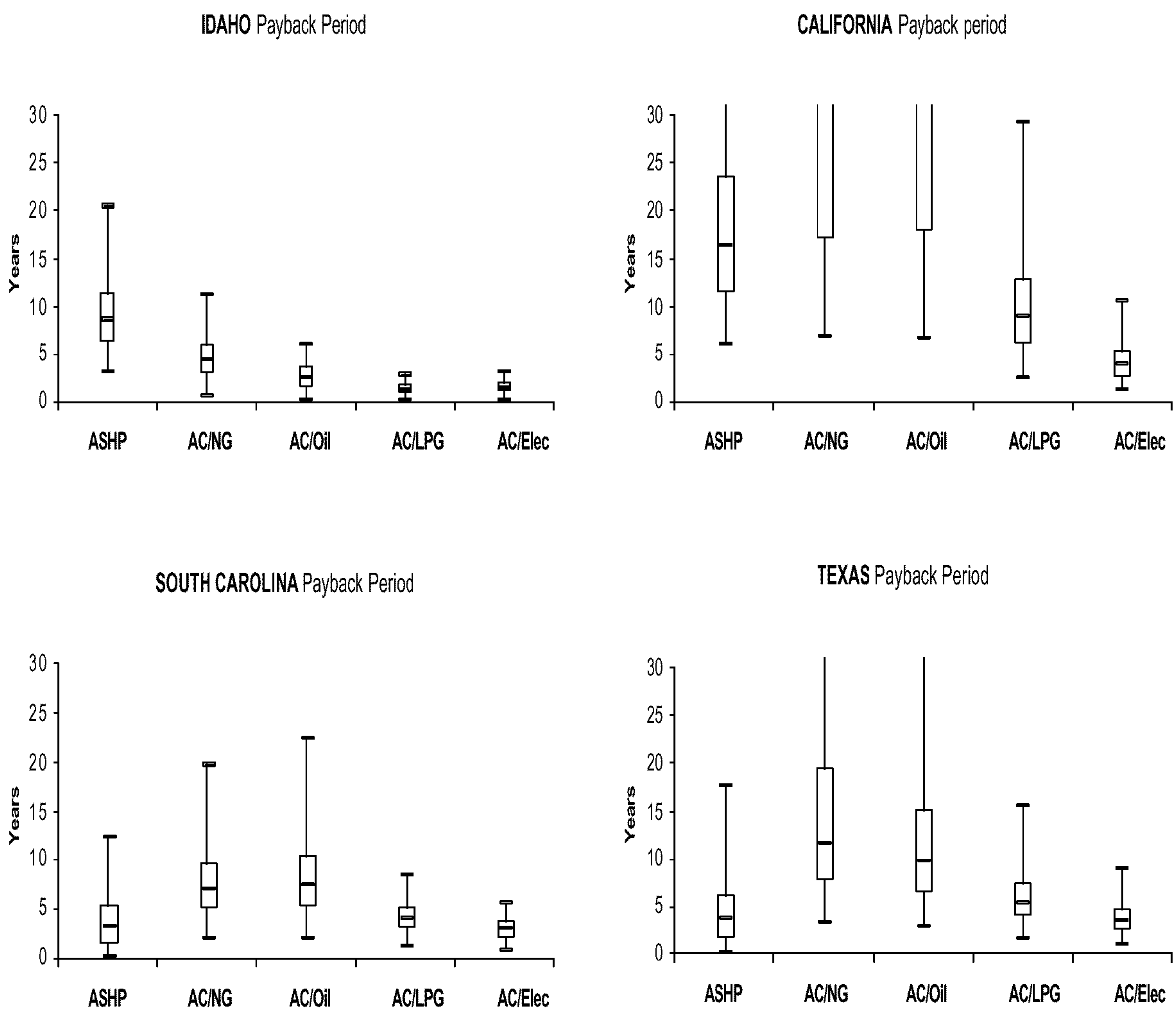


Figure 22. Commercial HVAC Payback Period for ID, CA, SC, and TX

The DOE reports that 53% of the residential heating systems in the U.S. are from natural gas furnaces, 29% from air and ground source heat pumps, 9% from fuel oil, and less than 9% for LPG (DOE, 1997). For commercial buildings with HVAC units less than 72,000 Btu/hr (those used in this study), the HVAC systems used for space conditioning are very similar to that of residential. Thus, the sensitivity analysis will only address the GSHP payback period relative to air-cooled AC with natural gas furnace heating. Figure 23 displays the GSHP payback period for each state relative to AC/NG systems. Because long payback periods are undesirable, the figure is truncated at 30 years to better visualize the payback periods for states with shorter payback periods.

The payback sensitivity analysis in Table 13 shows that the drilling cost associated with the vertical closed-loop GSHP typically has the most contribution to payback duration. Other start-up costs for a GSHP (such as the heat pump unit, pipe material, grout backfill, and antifreeze water fluid) contribute less than 5% of the total variance to payback periods and thus are not listed in Table 13. In states where natural gas prices are the largest contributor to variance, the natural gas price distributions are either much higher or lower than that of the electricity price distributions. For example, California has one of the highest electricity cost in the U.S., but has average natural gas prices; thus, the payback time for California tends to be very long.

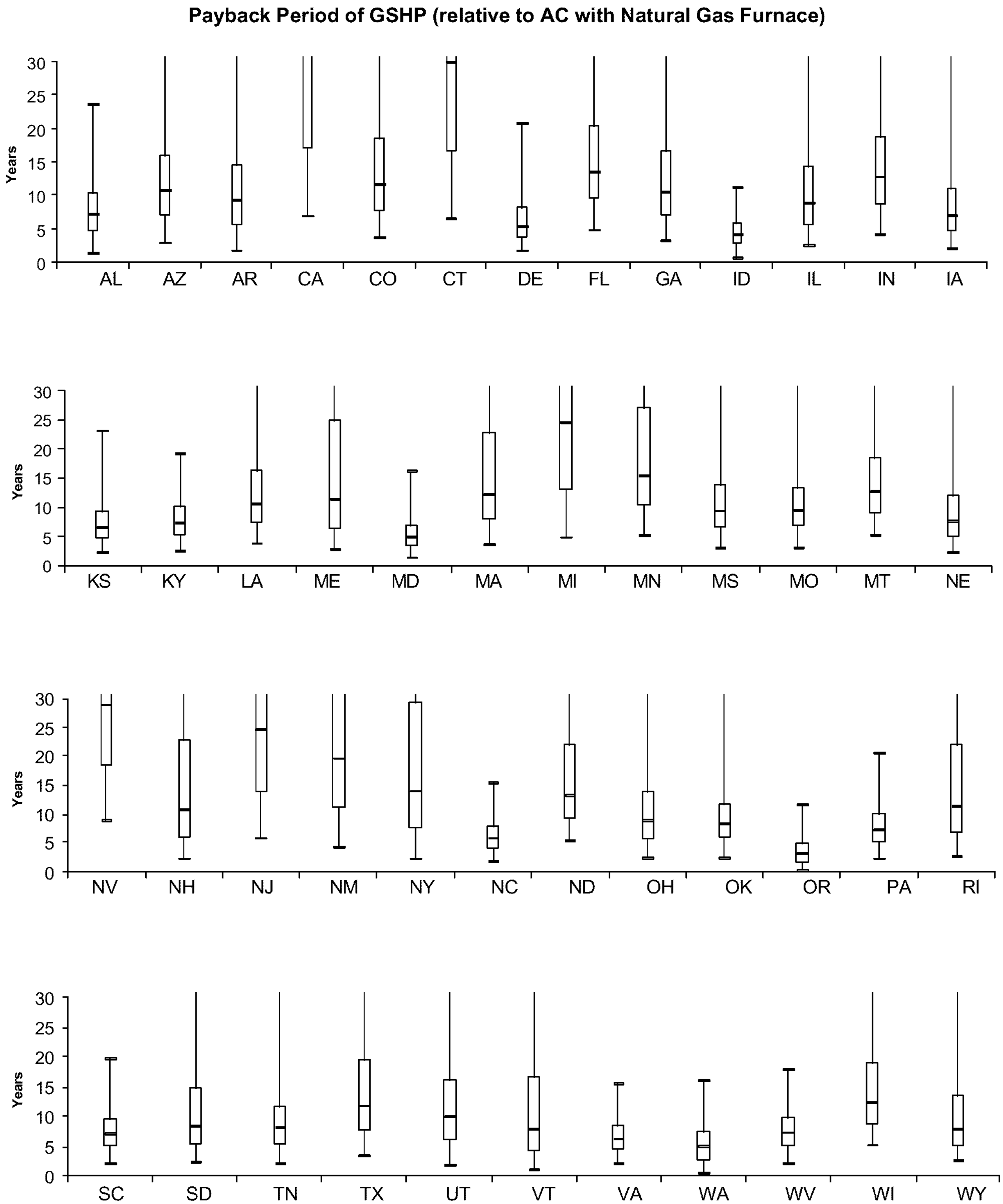


Figure 23. Payback Period for Commercial Vertical Closed-Loop GSHP Relative to Air-Cooled AC with Natural Gas Furnace

Table 13. Sensitivity Analysis for GSHP Payback Period Relative to AC with NG Furnace

State	GSHP Payback from AC/NG Furnace								
	GSHP Drilling Cost	NG Price	GSHP COP	GSHP EER	AC Start-up Cost	AC SEER	NG AFUE	Annual Cooling Hr	Electric Price
AL	54.8%			7.4%	9.5%	14.9%			
AZ	37.8%	7.6%	10.6%	9.7%		15.1%			
AR	39.0%	24.0%		7.3%	6.3%	11.8%			
CA	19.7%	22.5%	12.1%			8.5%		13.6%	
CO	34.9%	17.3%	21.3%				6.5%		7.2%
CT	72.7%				6.4%				
DE	29.9%	57.4%							
FL	23.2%			23.8%		42.4%			
GA	23.7%	39.4%		9.1%		13.2%			
ID	61.9%	8.6%			11.7%				
IL	30.0%	43.0%	8.7%						
IN	33.3%	26.3%	18.6%				5.3%		
IA	22.9%	49.2%	10.6%						
KS	42.2%	21.0%	10.5%						
KY	53.3%	18.7%	6.7%		5.9%				
LA	30.0%	6.5%		18.7%		31.2%			
ME	13.8%	67.3%	9.4%						
MD	48.9%	21.6%	6.4%		7.1%				
MA	20.3%	34.8%	20.5%				5.3%		13.6%
MI	32.8%	6.8%	39.1%						
MN	14.7%	50.1%	19.6%				7.0%		
MS	32.7%	10.7%		13.9%	6.3%	22.9%			
MO	47.8%	18.3%	6.4%		6.1%				
MT	20.8%	38.4%	20.4%				7.4%		10.9%
NE	28.7%	36.9%	13.3%						
NV	21.9%		29.8%	9.8%		13.4%	6.7%		
NH	38.7%	24.6%	18.1%						
NJ	78.3%				6.6%				
NM	19.2%	46.6%	15.1%						
NY	56.7%	8.8%	9.6%		7.1%				
NC	46.3%	12.0%	6.5%		8.7%	8.5%			
ND	10.3%	54.1%	20.3%				8.3%		
OH	34.2%	27.5%	18.6%				5.6%		
OK	38.4%	11.0%	8.8%		8.5%	12.2%			
OR	67.1%	15.8%			8.6%				
PA	55.7%	12.1%	9.6%		5.9%		5.3%		
RI	24.6%	22.0%	19.5%				7.6%		19.1%
SC	44.6%	7.7%		7.6%	12.3%	12.0%			
SD	19.2%	47.6%	17.8%				5.0%		
TN	39.9%	15.6%		6.9%	9.4%	10.4%			
TX	22.7%			16.6%		28.4%		10.1%	
UT	34.3%	13.9%	24.0%		7.1%		6.4%		
VT	29.9%	7.8%	35.8%						11.8%
VA	50.7%	18.9%	6.0%		6.8%				
WA	62.1%	7.0%	5.1%		7.4%				
WV	61.6%		9.0%		7.4%				
WI	17.6%	46.7%	20.5%				7.6%		
WY	20.0%	52.9%	14.1%						
USA	31.8%	32.2%	14.1%						

States with more land surface area, such as California, tend to have more variance attributed with their input variables (i.e., sub-surface ground temperatures, heating and cooling loads and hours), and thus the output box-and-whisker payback distributions encompass a much wider range. However, some relatively small states also have a wide output box-and-whisker payback distribution due to wide variability in utility cost (such as Rhode Island) or wide variability in labor and material cost coefficients (such as Vermont, which has little variability in utility cost relative to most other states).

GSHP Drilling Cost

Drilling cost is primarily driven by the required total loop length of the vertical closed loop GSHP. The impact that the cost of drilling has on the output may be dampened if the wide distribution associated with this variable is shortened. Because drilling cost was one of the largest contributors to payback periods, a sensitivity analysis was performed on the total loop length required. As expected, the thermal conductivity of the ground is the largest contributor to variance within the drilling cost (see Table 14). It is interesting that while the thermal conductivity of grout/backfill, ground temperatures, and inlet water temperatures play an influential role, they do not have the wide range of variability that the ground thermal conductivity value does. However, when a specific site is evaluated, the ground thermal conductivity will be known and therefore not be as influential on the payback period. Thus the grout/backfill thermal conductivity, ground temperatures, inlet and outlet water temperatures, flow rates, etc.; will become more influential to the outcome.

Table 14. Sensitivity Analysis for GSHP Total Loop Length

State	Total Loop Length				
	Thermal Conductivity		Ground	Inlet Cooling	Cooling
	Ground	Grout/Backfill	Temp	Water Temp	Load
AL	73.2%	5.8%		5.6%	
AZ	64.5%	5.0%	14.6%		
AR	73.9%	5.9%		6.0%	
CA	69.3%	6.2%	12.6%		
CO	67.3%		16.3%		
CT	75.3%	9.0%			
DE	72.4%	6.4%			7.1%
FL	76.3%				
GA	75.7%	6.1%		5.2%	
ID	79.9%	6.2%			
IL	76.4%	7.2%			
IN	75.5%	7.3%			
IA	75.6%	7.4%			
KS	78.5%	6.4%			
KY	73.4%	7.1%		5.6%	6.4%
LA	75.3%	6.5%		5.5%	
ME	75.0%	5.2%	5.5%		
MD	74.7%	6.4%			
MA	77.6%	6.5%			
MI	78.5%	5.5%			
MN	68.7%		13.7%		
MS	74.8%	6.6%		5.0%	
MO	75.8%	7.9%			
MT	71.8%	5.0%	9.7%		
NE	79.6%	8.2%			
NV	72.0%	6.5%			7.1%
NH	79.6%				
NJ	78.1%	7.2%			
NM	77.8%	8.5%			
NY	77.3%	7.0%			
NC	75.3%	6.9%		5.1%	
ND	68.8%		13.7%		
OH	79.9%	6.3%			
OK	74.7%	6.7%		5.3%	
OR	79.5%	6.6%			
PA	77.6%	8.2%			
RI	80.3%	6.8%			
SC	76.1%	7.0%			
SD	77.2%	6.9%			
TN	73.0%	7.0%		5.2%	
TX	69.5%	5.0%	6.7%		6.7%
UT	78.8%	7.1%			
VT	77.0%	6.7%			
VA	72.0%	6.3%		5.1%	
WA	70.0%	6.2%			
WV	77.0%	6.2%		5.1%	
WI	71.8%	5.2%	7.2%		
WY	70.0%	6.4%	9.6%		
USA	77.3%	8.2%			

Payback Period Sensitivity Investigation

Through the initial sensitivity analysis, it is clear that utility prices, ground thermal conductivity, and coefficient of performance contribute the largest variability to the payback period in most states. To better understand how each of these variables contributes to the payback period, the model was reevaluated by using a single fixed low and high value for each of these variables. The states average electricity and natural gas prices in 2000 were individually and cumulatively doubled while keeping the original distributions for all other input variables. For ground thermal conductivity, the lowest rock and highest soil thermal conductivity values in the U.S. were selected (0.6 and 2.2 Btu/hr-ft-°F, respectively). Note that the original uniform ground thermal conductivity distribution ranged from 0.3 to 3.6 Btu/hr-ft-°F when using the lowest and highest ground thermal conductivity values possible. The process is repeated for the minimum and maximum GSHP efficiencies observed from the 195 GSHP units reviewed in this study. Figures 24 through 27 display the payback period sensitivity results for Idaho, California, South Carolina, and Texas. In these figures, the base case represents the original simulation output before values of interest are held constant.

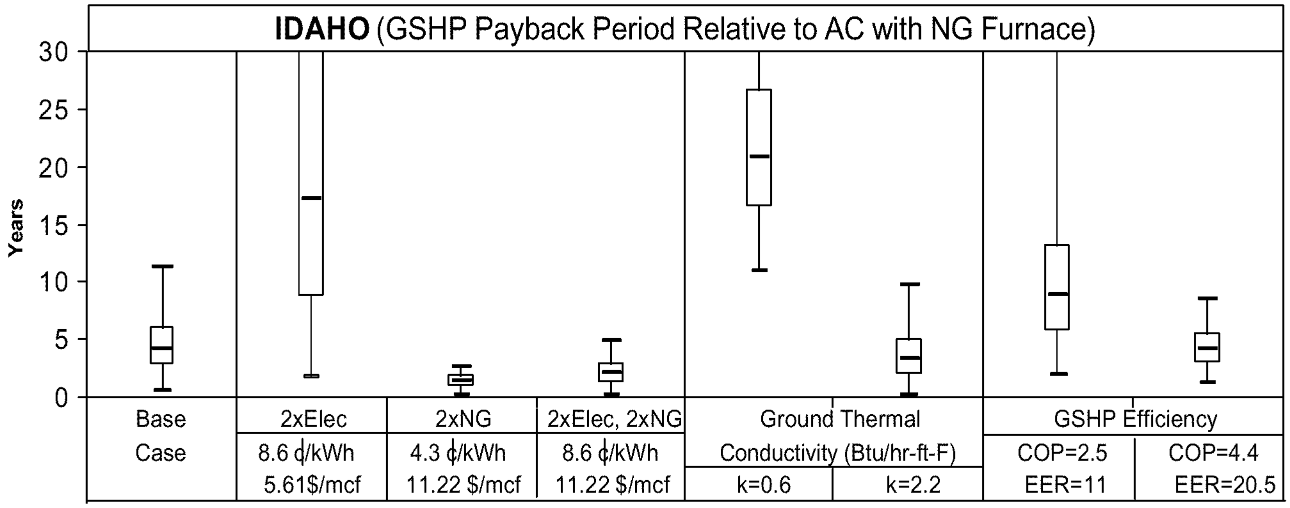


Figure 24. Vertical Closed-loop GSHP Payback Period Sensitivity Investigation for Idaho

It is evident that payback periods in Idaho would be substantially longer if the price of electricity were to double. This occurs because GSHP rely only on electrical power, unlike AC/NG systems that use both electricity and natural gas. It is also clear that if the price of natural gas were to double, the payback would be reduced more than those in the base case. It is interesting to note that if both electricity and natural gas prices double the payback distribution is generally shorter than the base case. The ground thermal conductivity also has a large impact on the payback period; however, the coefficient of performance selected does not contribute to the payback period as much as the utility price or ground thermal conductivity.

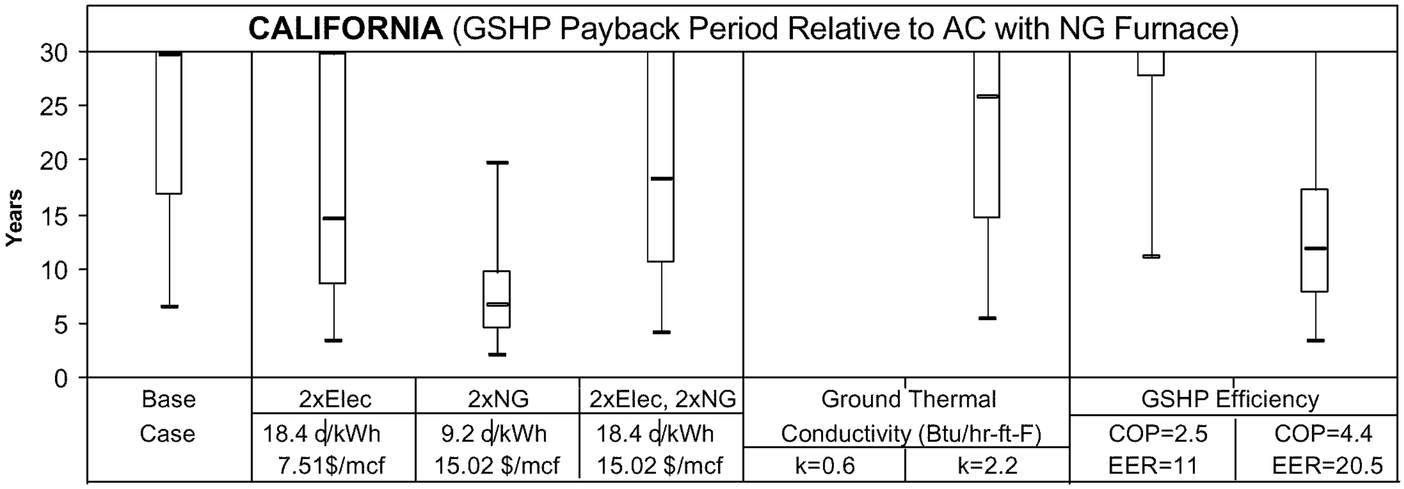


Figure 25. Vertical Closed-loop GSHP Payback Period Sensitivity Investigation for California

The payback periods for California are extremely long, unless the natural gas prices are doubled. When the electricity price is doubled, the payback period actually decreases from that of the base case even though GSHPs only use electricity. This occurs because the conventional HVAC air-cooled AC is less efficient during the cooling season and consumes more energy at the higher electricity price. It is also evident that when the ground thermal conductivity value is poor (k=0.6), the payback will be much greater than 30 years. The wide payback period probability distribution for California may also be influenced by the size of the state, as it has a wide range of temperature variation from that of smaller states. Figures 26 and 27 display similar behaviors of increasing or decreasing payback periods depending the input variables selected.

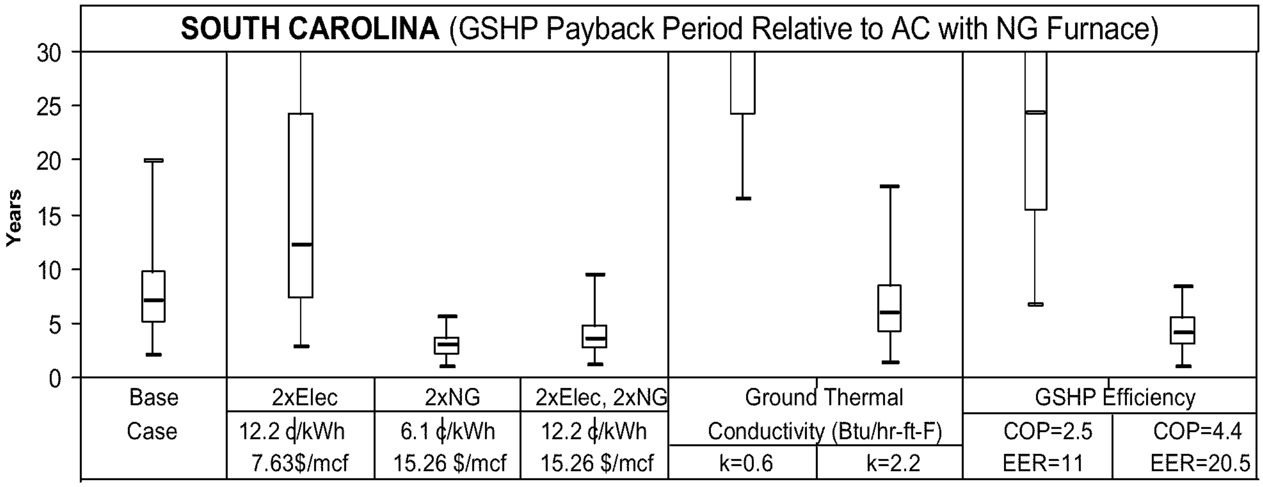


Figure 26. Vertical Closed-loop GSHP Payback Period Sensitivity Investigation for South Carolina

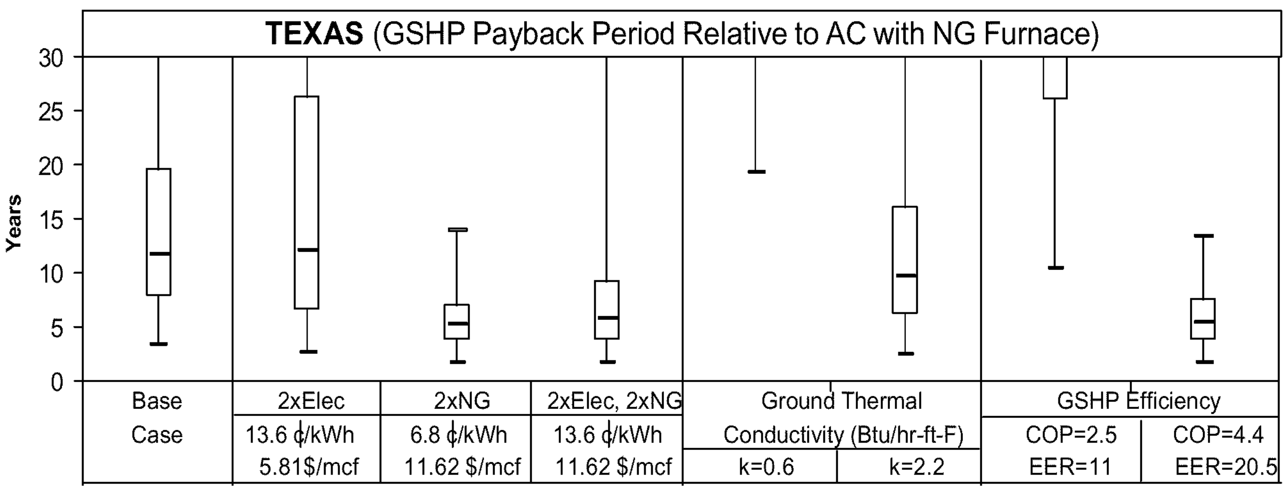


Figure 27. Vertical Closed-loop GSHP Payback Period Sensitivity Investigation for Texas

Validation of the Simulation Model Using Fort Polk Case Study

Fort Polk, Louisiana is the location of one of the world's largest geothermal heat pump projects. At Fort Polk, vertical closed-loop GSHP systems were installed in 4,003 military family housing units, where the average housing unit is 1,400 square feet. Fort Polk's total pre, and post, retrofit annual energy consumption, GSHP loop length, and GSHP installation cost, have been evaluated by Oak Ridge National Laboratories (Hudghes and Shonder, 1998).

Site-Specific Input and Output Variables for Fort Polk

Based on the Oak Ridge National Laboratories Study, the energy consumption attributed solely to space conditioning was obtained by monitoring 200 military family housing apartments. In these housing units, 34.7% of the total post-retrofit energy consumption was attributed to space conditioning. The total post-retrofit annual energy consumption for all 200 housing units was 2,001,455 kilowatthour (kWh) (approximately 10,007 kWh per housing unit); thus, the annual energy consumption for space conditioning of each housing unit is estimated to be 3,475 kWh. The average price of electricity for Fort Polk during the evaluation was reported as six cents per kWh; therefore, the annual operating cost of each housing unit is approximately $208. The average housing unit is conditioned by 1.65 tons of cooling and 12,000 Btu/hr of heating. For Fort Polk, an average of 275 ft of bore was required per ton. Thus, the total loop length required per housing unit is 989 ft (Fort Polk design includes 16 ft between boreholes and 25 ft between the borehole and the GSHP unit). The average

equipment installation cost for the conditioning system (labor and material) is estimated at $4,300 per housing unit.

The site-specific Monte Carlo simulation input variables used for Fort Polk are listed in Table 15. All other input variable distributions, such as ground water movement, U-tube pipe placement within the borehole, cooling and heating hours for Louisiana, etc., retain their original distributions given in Tables 4 and 5. The simulation model predicts the pipe diameter to be one inch nominal outside diameter, which is the pipe diameter used at Fort Polk.

Table 15. Fort Polk Site-Specific Input Variables

Variable	Single Value	Uniform Distribution		Units
		Min	Max	
Cooling Load	1.65	-	-	tons
Heating Load	12,000	-	-	Btu/hr
Energy Efficiency Ratio (EER)	15.4	-	-	Btu/Whr
Coefficient of Performance (COP)	3.5	-	-	unitless
Ground Thermal Conductivity	-	0.964	1.156	Btu/hr-ft-F
Ground Thermal Difusivity	0.96	-	-	ft^2/day
Ground Temperature	-	67.8	69	F
Grout/backfill Thermal Conductivity	-	0.35	0.45	Btu/hr-ft-F
Part Load Factor	-	0.52	0.73	unitless
Number of bores per parallel pipe	2	-	-	unitless
Design flow rate per ton	3	-	-	gpm/ton
Source: (Hudghes and Shonder, 1998)				

Validation Results and Discussion

The actual average output values documented for Fort Polk are shown in Figure 28, along with the Monte Carlo simulation output probability distributions computed with the Fort Polk site-specific data provided by Oak Ridge National Laboratories. With the exception of the total loop length per housing unit, all of the Fort Polk output variables were within the 25th to 75th percentile.

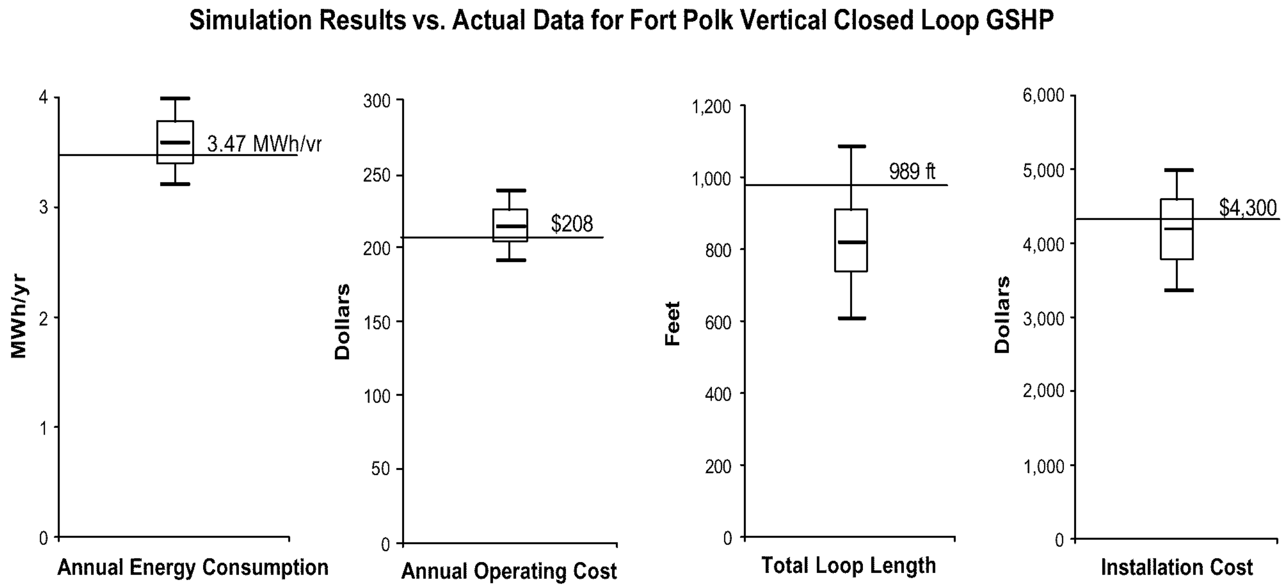


Figure 28. Validation of Simulation Model Using Fort Polk Case Study Data

The loop length at Fort Polk may be slightly longer than those reported by the Monte Carlo simulation due to a conservative loop design. It is possible that the Fort Polk design was based on minimal groundwater movement, or under the assumption that the U-tube pipes within the boreholes would typically be touching each other (as opposed to being centered or touching the borehole walls). Relaxing the original uniform distributions for groundwater movement and U-tube pipe location with the borehole, and replacing the input values with minimum groundwater movement and U-tube pipes touching each other, yields a distribution that captures the average Fort Polk total loop length within the 25th to 75th percentile (see Figure 29). Applying actual data from Fort Polk, supports the Monte Carlo simulation output used in this study.

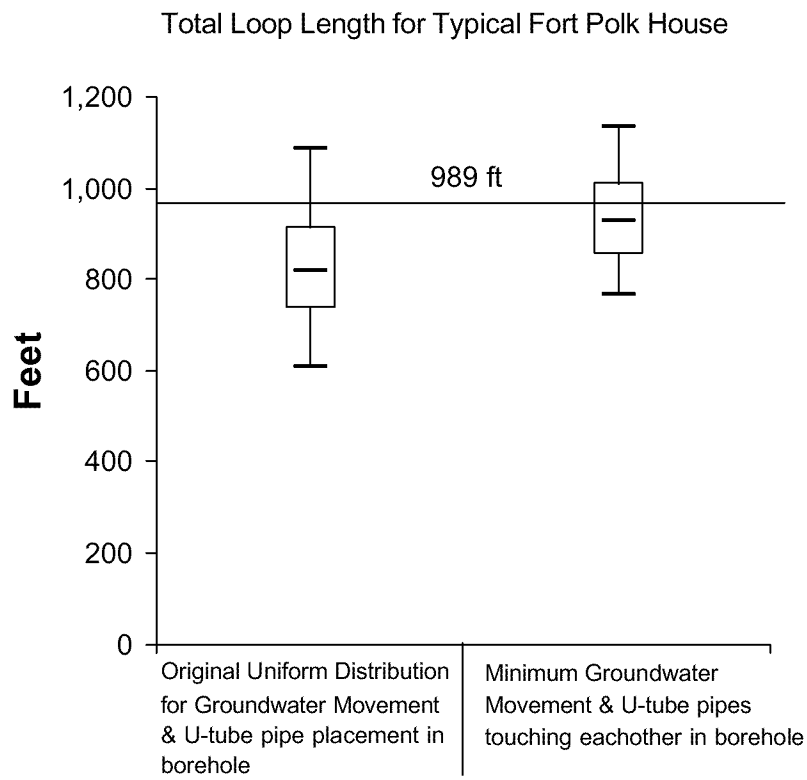


Figure 29. Effect of Groundwater Movement & U-Tube Placement in Borehole

V. Discussion

Geographic Highlights

The Monte Carlo simulation used in this study provided insight into which states offer more favorable input variables. Input variables that yield lower operating and installation cost for the vertical closed loop GSHP systems provide shorter payback periods relative to air-cooled AC with natural gas furnaces. Figure 28 displays a map of the states in which the 50th percentile payback values were less than 10 years. Given each state's probability distribution for climatic data, utility prices, and material and labor cost, some states naturally yielded shorter payback periods. It is interesting to note that the states with payback periods less than 10 years appear to be the location of the majority of commercial GSHP contractors in the U.S., with the exception of some of the northwestern states (Washington, Oregon, and Idaho) which appear to be good candidates for GSHP implementation (GeoExchange, 1999).

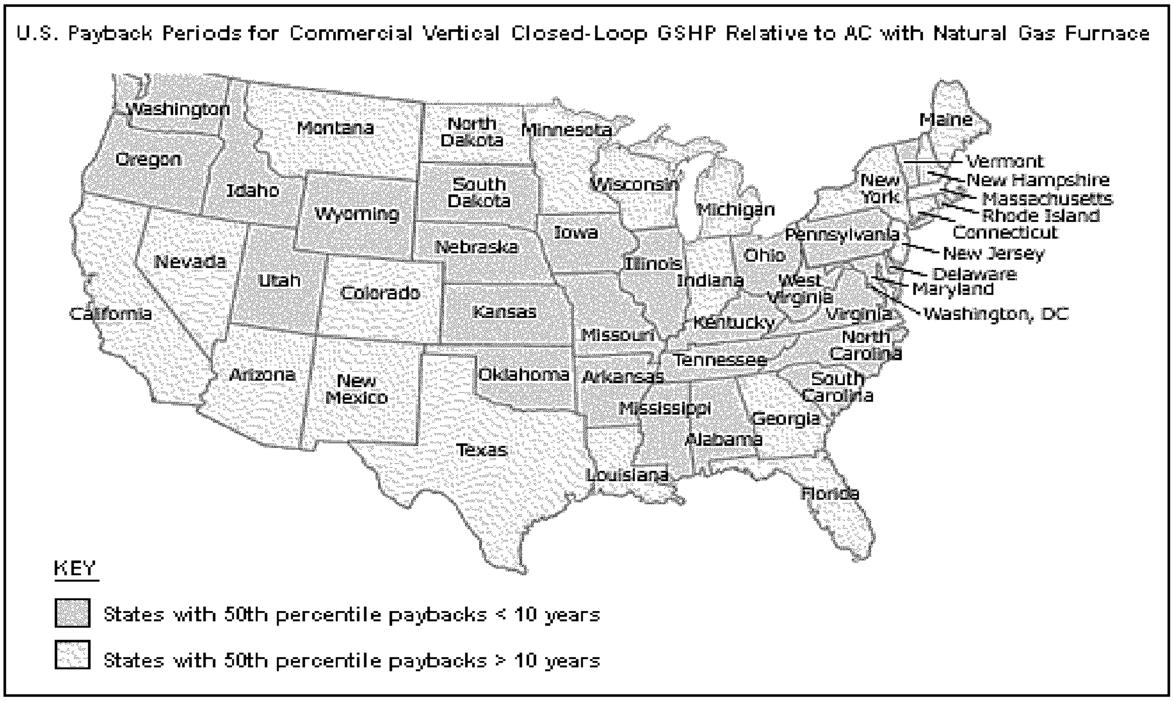


Figure 30. U.S. Map of Payback Periods for Commercial Vertical Closed-Loop GSHP relative to AC/NG System

According to the sensitivity analysis, the length of the GSHP loop is a main driver for the installation cost (thus payback period) and is primarily influenced by the ground thermal conductivity. Because the ground thermal conductivity is highly variable, a single probability distribution was used for the entire U.S. instead of varying the distributions from state to state. Therefore, the actual paybacks at a given location may be substantially more or less than the 50th percentile; however, all possible payback outcomes are captured within the Monte Carlo payback probability distributions for each state shown in Figure 23 of this study.

Limitation and Future Research

Several items were not included in this study that could potentially impact the results. These limitations lend themselves to opportunities for future research. These limitations are listed below.

1. Utility companies, states, and city regulatory offices often provide discounts for using Geothermal Heat Pumps. The discount can take the form of reduced electric utility rates, refunds for a percentage of the equipment cost, reduced mortgage rates for purchasing homes or businesses, and/or income tax credits. These discounts were not included because they are temporary incentives and vary greatly for each location.
2. Total energy and price reductions would also be realized if the GSHP was used to supplement the hot water heating.
3. The borehole drilling cost is based on a single project; however, monetary savings will result if drilling is performed for other projects within the same location because the equipment and laborers are already in place.
4. The increase in price that is typically associated with purchasing a more efficient HVAC unit of the same type is not included.
5. Manufactured efficiencies are based on a mild climate; thus, they are not a perfect representation of actual performance.
6. The ground thermal conductivity and thermal diffusivity values include a wide distribution that covers a wide variety of soil, rock, moisture and density conditions. These site-specific values should be individually evaluated for each project. This is especially important considering the sensitivity analysis

results show that the thermal conductivity value has the greatest influence on the loop length, which affects the installed cost and thus contributes directly to the payback period.

7. The analysis uses current federal standards for the minimum efficiency ratings. The payback periods will be different if comparing a geothermal system to a conventional system that has been in place for many years. This is because past efficiency standards and technology were not in place to support the high efficiency ratings that are required today.

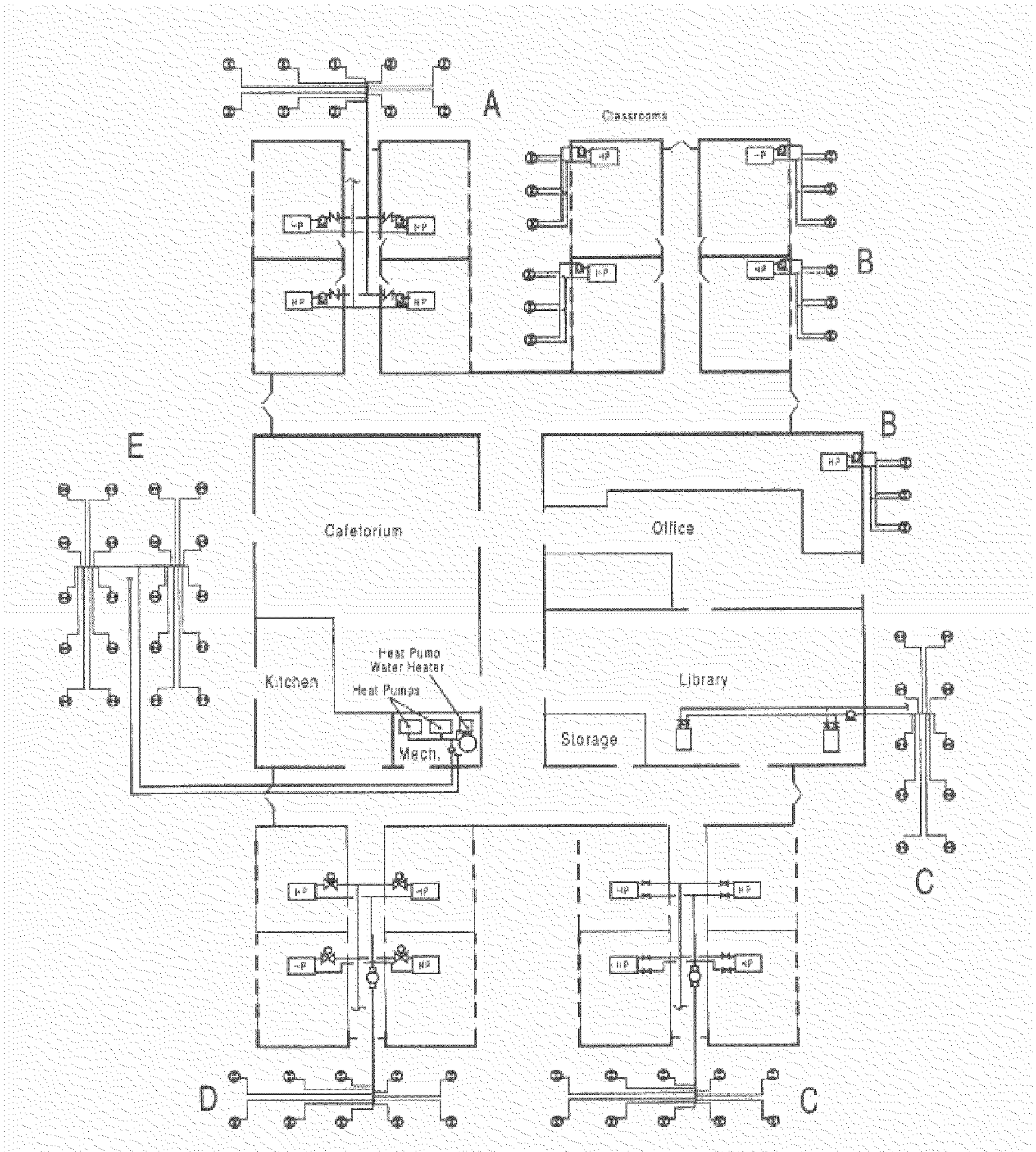
Conclusions

The state-by-state analysis performed in this evaluation is based on the minimum and maximum values obtained from cities within that state; therefore, the input parameters have a large range of possible values, i.e., utility rates, state cost indexes, heating and cooling loads, and heating and cooling hours. This is acceptable when comparing states with each other but should not be used when performing an analysis for a specific job site. However, the model created for this study can easily be adapted to any specific job site, or building type, by inserting the site-specific variables expected at that location. For example, ground thermal properties can be obtained from ground sampling, the grout backfill properties may be known, and the local utility rates and city cost index would be known. With this in mind, a better estimate for the energy consumption, annual operating cost, life cycle cost, and payback periods can be obtained for the location of interest.

Regardless of the conventional system chosen, the state analysis shows that the vertical closed-loop ground source heat pump has the highest probability of using less energy and having a lower operating and life cycle cost than the conventional HVAC systems; however, initial installation cost are typically twice that of conventional HVAC systems. When comparing vertical closed-loop GSHPs to air-cooled AC with natural gas furnaces, these savings are typically not substantial enough to provide payback periods less than four years, as is often quoted. The average 50^{th} percentile payback period in the U.S. is approximately 9 years and varies vastly between states. Under the right conditions, geothermal heat pumps are a great alternative to conventional HVAC systems. Site specific variables such as ground thermal conductivity, utility prices, and GSHP efficiency ratings, greatly impact the attractiveness of the GSHP.

Appendix A: Alternatives for Closed-Loop GSHP Design

(Kavanaugh and Rafferty, 1997)



Alternatives to central loop ground-coupled heat pumps.
A: One local loop, multiple heat pumps with pump and check valve on each unit
B: Multiple individual loops, heat pumps, and circulator pumps
C: Multiple units with one local pump that operates when one or more units is on
D: Multiple units with two-way valves, one local loop, and VS pump
E: Heat pumps and water heater on same loop to balance local load

Appendix B: Commercial 2000 s.f. Office Building Characteristics

INTERNAL LOAD			
People			
Type	General Office Space		
Density	143 sq ft/person		
Sensible	250 Btu/hr per person		
Latent	200 Btu/hr per person		
Lighting			
Energy	0.3 W/sq ft		
Misc. Loads			
Type	Std Office Equipment		
Energy	0.5 W/sq ft		
THERMOSTAT			
Cooling dry bulb	75F		
Heating dry bulb	68F		
Relative humidity	50%		
Cooling driftpoint	90F		
Heating driftpoint	55F		
AIR FLOW			
Ventilation			
20 cfm/person			
Infiltration			
0.6 air changes/hr			
BUILDING			
Length	50	ft	
Width	40	ft	
Wall Height	10	ft	
Plenum	2	ft	
Acoustic Ceiling Resistance			0.06
CONSTRUCTION			U-factor (Btu/h-ft^2-F)
Floor	4" LW Concrete		0.21
Roof	4" LW Concrete		0.21
Wall	Frame Wall, 3" Ins		0.08
Partition	3/4" Gyp Frame		0.39
Window	35% of wall		
	Double Clear 1/4"		0.60
Shading	Coefficient		0.82
	No Overhang		

Note: Building characteristics are default settings of Trane Trace 700 Software

Appendix C: Cities Used as Proxy for State Heating and Cooling Loads

State	City	State	City
Alabama	Birmingham	Missouri	Kansas City
Arizona	Phoenix		Springfield
	Tuscon	Montana	Billings
Arkansas	Little Rock		Great Falls
California	Los Angeles	Nebraska	Omaha City
	Sacramento	Nevada	Las Vegas
Colorado	Denver		Reno
	Colorado Springs	New Hampshire	Concord
Connecticut	Bridgeport	New Jersey	Newark
	Hartford	New Mexico	Albuquerque
Delaware	Wilmington	New York	New York
	Dover		Buffalo
Florida	Jacksonville	North Carolina	Charlotte
	Miami	North Dakota	Fargo
	Panama City		Minot
Georgia	Atlanta	Ohio	Columbus
	Augusta	Oklahoma	Oklahoma City
Idaho	Boise	Oregon	Portland
Illinois	Chicago	Pennsylvania	Philadelphia
	E. St. Louis		Pittsburg
Indiana	Indianapolis	Rhode Island	Providence
	Fort Wayne	South Carolina	Columbia
Iowa	Des Moines	South Dakota	Sioux Falls
	Sioux City		Rapid City
Kansas	Wichita	Tennessee	Memphis
	Topeka		Nashville
Kentucky	Louisville	Texas	Houston
	Lexington		San Antonio
Louisiana	New Orleans		Dallas/Fort Worth
	Baton Rouge		Lubbock
Maine	Portland		Corpus Christi
	Loring AFB	Utah	Salt Lake
Maryland	Baltimore	Vermont	Montpellier
Massachusetts	Boston	Virginia	Richmond
Michigan	Detroit		Norfolk
	Lansing	Washington	Seattle
Minnesota	Minneapolis		Spokane
	Duluth	West Virginia	Charleston
Mississippi	Jackson	Wisconsin	Milwaukee

Appendix D: State Heating & Cooling Loads, Hours, and Ground Temperature Distributions for 2000 s.f. Office Building

State	Abv.	Cool Load (Tons)		Heat Load (Mbtu/hr)		Heating Hours		Cooling Hours		Ground Temp (F)	
		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Alabama	AL	4.6	5.6	22.0	26.8	1250	1750	1300	1900	59	67
Arizona	AZ	4.4	6.4	23.1	28.8	1750	2250	900	1300	52	75
Arkansas	AR	5.2	6.4	26.7	32.7	1615	1785	1300	1500	60	67
California	CA	3.6	4.4	7.3	25.7	1750	3250	200	1300	57	79
Colorado	CO	3.2	4.2	43.1	49.5	2250	2750	500	700	42	57
Connecticut	CT	4.1	5.2	31.7	44.4	2250	2750	500	700	47	52
Delaware	DE	3.9	5.7	31.6	39.3	2090	2310	855	945	52	57
Florida	FL	5.0	6.4	0.9	20.5	250	750	1900	2500	69	77
Georgia	GA	4.1	5.4	23.1	30.0	1250	1750	1100	1700	62	67
Idaho	ID	3.3	4.1	33.7	41.1	2250	2750	500	700	46	53
Illinois	IL	3.2	5.5	31.1	52.1	2090	2310	700	1100	51	57
Indiana	IN	4.0	5.2	34.9	44.2	2090	2310	700	900	52	57
Iowa	IA	4.1	5.1	42.7	63.7	2090	2310	700	900	47	54
Kansas	KS	3.8	5.5	35.0	56.9	1750	2250	900	1100	54	57
Kentucky	KY	3.8	5.2	29.6	38.0	1750	2250	900	1100	57	60
Louisiana	LA	4.9	6.1	15.3	21.0	1140	1260	1500	2100	66	70
Maine	ME	2.3	3.7	41.0	52.4	2565	2835	200	500	42	48
Maryland	MD	3.9	4.7	28.4	34.8	2090	2310	855	945	47	52
Massachusetts	MA	3.2	4.0	38.9	47.5	2250	2750	475	525	47	52
Michigan	MI	3.0	4.7	34.4	46.1	2750	3250	500	700	42	50
Minnesota	MN	2.5	4.6	46.8	61.2	2750	3250	200	700	37	47
Mississippi	MS	5.0	6.2	21.2	25.9	1250	1750	1300	1900	62	70
Missouri	MO	4.6	5.7	31.2	38.5	1750	2250	1045	1155	54	58
Montana	MT	3.1	4.4	47.5	59.8	2250	2750	200	500	42	50
Nebraska	NE	4.1	5.1	39.9	48.7	2090	2310	700	900	51	53
Nevada	NV	3.7	6.1	25.7	36.6	2090	2310	700	1300	47	69
New Hampshire	NH	3.2	3.9	37.8	46.2	2565	2835	475	525	42	47
New Jersey	NJ	4.1	5.0	35.6	43.6	2090	2310	665	735	52	57
New Mexico	NM	4.0	4.8	32.8	40.0	1750	2250	700	1300	52	67
New York	NY	2.5	4.2	32.0	47.3	2250	2750	500	700	46	50
North Carolina	NC	4.1	5.1	26.4	32.2	1615	1785	1100	1300	60	65
North Dakota	ND	3.4	4.7	56.4	70.5	2565	2835	200	500	37	47
Ohio	OH	3.6	4.4	35.1	42.9	2090	2310	700	900	51	56
Oklahoma	OK	4.9	5.9	30.6	37.4	1615	1785	1100	1300	62	65
Oregon	OR	2.4	3.0	25.8	31.6	2250	3250	200	700	52	56
Pennsylvania	PA	3.2	4.7	30.5	44.0	2090	2310	665	735	52	55
Rhode Island	RI	3.3	4.1	36.5	44.7	2090	2310	475	525	47	52
South Carolina	SC	4.9	5.9	23.2	28.4	1250	1750	1100	1300	62	67
South Dakota	SD	3.8	5.1	46.3	57.9	2250	2750	500	700	45	50
Tennessee	TN	4.3	5.9	24.5	33.3	1615	1785	1100	1300	59	63
Texas	TX	4.2	6.5	15.8	41.1	750	1750	1100	2500	62	75
Utah	UT	3.3	4.1	37.0	45.2	2090	2310	700	900	52	57
Vermont	VT	3.2	3.9	37.8	46.2	2565	2835	475	525	42	47
Virginia	VA	4.1	5.3	27.3	36.0	1750	2250	855	945	52	61
Washington	WA	2.4	3.2	21.9	45.1	2250	3250	200	700	48	53
West Virginia	WV	3.8	4.6	27.9	34.1	2090	2310	855	945	52	58
Wisconsin	WI	3.1	3.9	49.0	67.8	2750	3250	200	500	42	49
Wyoming	WY	2.8	3.4	40.3	49.3	2250	2750	475	525	42	50

Appendix E: Ground Source Heat Pump Cost from RS Means 2000 Facility Construction Unit Price Book

VERTICAL CLOSED LOOP GSHP COST				
Geothermal Heat Pump Unit*				
Cooling (Tons)	Heating (Mbtu/hr)	Cost Material	Labor	Total
1	13	$965	$241	$1,206
1.5	17	$1,150	$268	$1,418
2	19	$1,225	$284	$1,509
2.5	25	$1,300	$300	$1,600
3	27	$1,350	$345	$1,695
3.5	29	$1,450	$370	$1,820
4	31	$1,750	$400	$2,150
5	29	$2,125	$535	$2,660
7.5	35	$2,425	$805	$3,230
8.5	40	$6,900	$830	$7,730
10	50	$7,600	$910	$8,510

Loop Pump**			
hp	Material	Labor	Total
0.083	$197	$80	$277
0.125	$330	$80	$410
0.333	$365	$80	$445

Polyethylene Piping***			
Diameter (inches)	Material ($/ft)	Labor ($/ft)	Total ($/ft)
0.75	$0.23	$1.15	$1.38
1	$0.37	$1.24	$1.61
1.25	$0.56	$1.29	$1.85
1.5	$0.74	$1.34	$2.08

Bore Hole Drilling****			
Labor ($/ft)	Distribution	1 drill rig	1796
		1 light truck, 3 ton	180
$7.55	± 50%	Total equip. per day:	$1,976

Grout Backfill*****					
Granular Bentonite 50lb bags			Silica Sand (no hauling) 50lb bags		
Labor ($/bag)	Material ($/bag)	Total ($/bag)	Labor ($/hr)	Material ($/bag)	Total ($/bag)
$2.00	$11.65	$13.65	$2.00	$4.18	$6.18

All values are uniformly distributed with ± 10% in simulation unless otherwise noted.
* Packaged (not including ground loop, Heat @ 75F)
**Circulating heated or chilled water app., in line, 3/4" to 1-1/2" size, flanged connection, cast iron
***Not including excavation or backfill, 160 PSI
****Domestic water wells drilled 4" to 6" diameter
*****Grouter Handling Rate, Bags/hr = 10
Quantity of bentonite & sand depends on grout/backfill thermal conductivity selected by the model

Appendix F. Conventional HVAC Cost from RS Means 2000 Facility Construction Unit Price Book

CONVENTIONAL HVAC SYSTEM COST*

Air-Source Heat Pump (ASHP)**

Split System (outdoor condenser, inside air handler)					*Packaged System* (outdoor single unit condenser w/ air handler)				
Cooling (Tons)	Heating (Mbtu/hr)	Material	Labor	Total	Cooling (Tons)	Heating (Mbtu/hr)	Material	Labor	Total
2	8.5	$2,100	$400	$2,500	2	6.5	$2,525	$320	$2,845
2.5	10	$2,375	$480	$2,855	2.5	8	$2,875	$345	$3,220
3	13	$2,700	$605	$3,305	3	10	$3,025	$400	$3,425
3.5	18	$3,275	$645	$3,920	3.5	11	$3,425	$480	$3,905
4	24	$3,650	$805	$4,455	4	13	$3,800	$505	$4,305
5	27	$4,275	$965	$5,240	5	27	$4,375	$740	$5,115
7.5	33	$6,575	$1,600	$8,175	7.5	35	$8,225	$1,200	$9,425
10	50	$8,500	$1,975	$10,475	10	45	$10,600	$1,875	$12,475

Furnaces (no cooling)

Electric Resistance				**Natural Gas*****				**Fuel Oil******	
Heating (Mbtu/hr)	Material	Labor	Total	Heating (Mbtu/hr)	Material	Labor	Total	Heating (Mbtu/hr)	Total
10.2	$315	$120	$435	7.7	$400	$69	$469	7.7	$563
17.1	$330	$125	$455	14	$430	$75	$505	14	$605
27.3	$350	$131	$481	24	$520	$97	$617	24	$740
34.1	$405	$137	$542	49	$515	$121	$636	49	$763
51.6	$440	$143	$583	60	$580	$127	$707	60	$848
68.3	$610	$150	$760	75	$615	$134	$749	75	$899
85.3	$670	$159	$829						

Air-Cooled AC (no heat)*****

*Split System*********						*Packaged System*			
Cooling	Condensing Unit		Air Handler			Cooling			
(Tons)	Material	Labor	Material	Labor	Total	(Tons)	Material	Labor	Total
2	$810	$230	$870	$455	$2,365	3	$4,400	$480	$4,880
2.5	$955	$284	$870	$455	$2,564	4	$4,775	$605	$5,380
3	$1,100	$370	$870	$455	$2,795	5	$5,525	$625	$6,150
3.5	$1,200	$440	$870	$455	$2,965	6	-	-	$7,070
4	$1,450	$535	$870	$455	$3,310	7.5	$7,500	$835	$8,335
5	$1,700	$805	$870	$455	$3,830				
7.5	$3,825	$875	$870	$455	$6,025				

All values are uniformly distributed with ± 10% in simulation
* Model averages the price of the split and packaged unit based on unit size selected
**Not including interconnecting tubing, curbs, pads, or ductwork.
Supplementary electric heat coil included.
***Not including flue piping for gas and oil systems
**** Prices for oil furnace units less than 56 Mbtu/hr are not listed and thus extrapolated values
*****Including compressor, standard controls, but not interconnecting tubing
******Air Handler Unit (AHU) rated @ 2000 cfm (typical for 2000 sq ft office building)
AHU includes cooling/heating coil, filters, mixing box. Single zone, constant volume

Appendix G: State Cost Coefficient Distributions from RS Means 2000 Facility Construction Unit Price Book

State	Labor State Cost Index		Total State Cost Index	
	Min	Max	Min	Max
Alabama	52.8	77.7	75.2	87.5
Arizona	40.1	64.4	67.2	80.8
Arkansas	68.2	77.8	84.8	89.8
California	106.9	136.6	105.5	123.8
Colorado	63.3	85.9	84.3	94.2
Connecticut	102.8	111.3	102.3	107.0
Delaware	100.1	100.2	99.4	99.7
Florida	44.6	74.6	73.1	87.7
Georgia	36.5	80.9	67.7	89.1
Idaho	53.5	90.5	79.7	102.5
Illinois	95.2	124.7	95.2	110.7
Indiana	80.1	101.8	87.7	99.6
Iowa	55.8	89.6	76.5	93.9
Kansas	53.9	91.1	76.4	94.5
Kentucky	51.7	99.3	72.7	96.3
Louisiana	58.0	69.2	78.0	85.3
Maine	55.0	82.9	77.7	91.7
Maryland	52.4	84.6	74.6	91.0
Massachusetts	101.6	131.1	100.3	116.6
Michigan	77.2	114.7	86.2	105.6
Minnesota	82.0	122.8	89.0	110.3
Mississippi	35.8	63.3	67.4	81.7
Missouri	67.8	110.4	81.6	103.2
Montana	87.1	89.9	92.7	96.1
Nebraska	42.9	79.4	72.1	90.2
Nevada	90.0	108.3	95.6	104.8
New Hampshire	57.0	85.1	77.7	93.6
New Jersey	111.7	122.3	106.1	112.4
New Mexico	72.2	81.1	85.5	91.2
New York	89.3	160.5	92.9	133.8
North Carolina	39.4	56.0	68.3	77.3
North Dakota	62.4	68.5	82.0	84.8
Ohio	75.6	106.4	87.2	102.4
Oklahoma	38.7	68.2	69.0	83.5
Oregon	98.7	108.2	97.2	106.0
Pennsylvania	89.3	124.8	91.6	111.9
Rhode Island	107.8	107.8	103.9	104.0
South Carolina	38.8	54.6	67.6	75.9
South Dakota	57.7	62.3	78.6	82.0
Tennessee	38.4	72.3	68.6	84.9
Texas	39.3	78.1	69.7	89.4
Utah	58.6	75.9	81.2	89.5
Vermont	37.9	64.9	69.3	83.7
Virginia	42.0	84.0	69.8	90.9
Washington	89.9	106.2	98.3	105.7
West Virginia	57.0	95.7	77.4	96.7
Wisconsin	84.3	102.3	90.8	100.8
Wyoming	52.3	64.5	77.2	83.1

Total state cost index includes labor, materials and equipment.

Appendix H. Annual Energy Consumption Output Data for Each State

STATE	ANNUAL ENERGY CONSUMPTION (MWhr/yr)					
AL	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	7.8	11.1	17.6	18.1	17.6	16.1
25%	9.1	12.8	20.0	20.4	20.0	18.2
50%	9.9	13.8	21.4	21.8	21.4	19.5
75%	10.7	14.9	22.8	23.2	22.8	20.8
97.5%	12.5	17.0	25.7	26.0	25.7	23.3
AZ	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	7.5	11.0	20.1	20.9	20.1	18.2
25%	8.8	12.6	22.8	23.4	22.8	20.3
50%	9.6	13.5	24.3	24.9	24.3	21.6
75%	10.3	14.6	25.9	26.4	25.9	22.9
97.5%	12.0	16.5	28.9	29.3	28.9	25.4
AR	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	9.3	13.4	22.8	23.7	22.8	20.8
25%	10.5	14.9	25.0	25.6	25.0	22.5
50%	11.1	15.7	26.2	26.7	26.2	23.6
75%	11.8	16.6	27.4	27.9	27.4	24.6
97.5%	13.3	18.2	29.7	30.0	29.7	26.4
CA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	3.2	4.4	8.5	8.8	8.5	7.6
25%	5.1	7.1	13.2	13.6	13.2	11.8
50%	6.2	8.8	17.0	17.5	17.0	15.0
75%	7.5	10.6	21.3	21.8	21.3	18.5
97.5%	10.1	14.2	28.9	29.7	28.9	25.0
CO	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	9.5	15.5	35.8	38.1	35.8	31.9
25%	11.1	17.3	40.0	41.5	40.0	34.6
50%	12.0	18.4	42.3	43.6	42.3	36.3
75%	13.0	19.5	44.9	45.8	44.9	38.0
97.5%	15.2	21.5	49.4	49.7	49.4	41.0
CT	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	8.3	12.9	28.7	30.1	28.7	25.2
25%	9.8	14.9	32.8	34.0	32.8	28.5
50%	10.8	16.1	35.8	37.0	35.8	30.9
75%	11.8	17.4	38.9	39.9	38.9	33.3
97.5%	13.8	19.7	44.1	44.7	44.1	37.1

LEGEND

GSHP	Ground Source Heat Pump (Vertical Closed-Loop)
ASHP	Air Source Heat Pump
AC/NG	Air-Cooled Air Conditioning with Natural Gas Furnace
AC/Oil	Air-Cooled Air Conditioning with Heating Fuel Oil Furnace
AC/LPG	Air-Cooled Air Conditioning with Liquid Petroleum Gas Furnace
AC/Elec	Air-Cooled Air Conditioning with Electrical Resistant Heating

DE	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	8.5	13.1	27.1	28.5	27.1	24.3
25%	9.8	14.6	29.9	30.9	29.9	26.2
50%	10.5	15.4	31.6	32.4	31.6	27.5
75%	11.3	16.3	33.3	34.0	33.3	28.8
97.5%	12.8	17.8	36.3	36.5	36.3	30.8
FL	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	7.8	10.6	11.2	11.2	11.2	11.0
25%	9.5	12.9	13.7	13.8	13.7	13.5
50%	10.4	14.2	15.3	15.4	15.3	15.1
75%	11.5	15.7	16.9	17.0	16.9	16.6
97.5%	13.8	18.4	20.1	20.1	20.1	19.6
GA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	6.9	9.9	16.8	17.3	16.8	15.3
25%	8.2	11.6	19.3	19.8	19.3	17.5
50%	8.9	12.6	20.8	21.3	20.8	18.8
75%	9.7	13.7	22.5	22.9	22.5	20.1
97.5%	11.4	15.7	25.5	25.7	25.5	22.7
ID	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	8.1	12.7	29.0	30.5	29.0	25.6
25%	9.3	14.3	32.4	33.6	32.4	28.1
50%	10.0	15.3	34.6	35.6	34.6	29.7
75%	10.9	16.2	36.8	37.7	36.8	31.4
97.5%	12.6	18.0	40.9	41.3	40.9	34.2
IL	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	8.3	12.8	27.2	28.3	27.2	24.1
25%	10.1	15.1	31.9	32.8	31.9	27.7
50%	11.3	16.8	35.9	36.8	35.9	31.1
75%	12.5	18.5	39.7	41.0	39.7	34.4
97.5%	14.9	21.2	45.3	45.8	45.3	38.3
IN	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	8.6	13.5	28.9	30.6	28.9	25.9
25%	10.0	15.1	32.0	33.1	32.0	27.9
50%	10.7	16.0	33.9	35.0	33.9	29.4
75%	11.5	16.9	36.0	36.8	36.0	31.0
97.5%	13.2	18.5	39.3	39.6	39.3	33.1
IA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	10.3	16.1	35.4	37.1	35.4	31.3
25%	12.0	18.3	40.0	41.3	40.0	34.6
50%	13.2	20.0	44.1	45.6	44.1	38.1
75%	14.5	21.7	48.3	49.8	48.3	41.6
97.5%	17.2	24.4	54.2	54.8	54.2	45.5
KS	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	9.0	13.7	27.6	28.8	27.6	24.5
25%	10.7	16.0	32.7	33.7	32.7	28.6
50%	11.8	17.6	36.5	37.6	36.5	31.8
75%	13.1	19.3	40.6	41.6	40.6	35.1
97.5%	15.5	22.3	47.2	47.9	47.2	40.2

KY	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	7.8	11.7	23.2	24.1	23.2	20.6
25%	8.9	13.2	26.2	27.1	26.2	23.1
50%	9.7	14.1	28.1	28.9	28.1	24.6
75%	10.4	15.1	30.0	30.7	30.0	26.1
97.5%	12.0	16.9	33.7	34.1	33.7	28.8
LA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	7.7	10.6	14.8	15.0	14.8	13.8
25%	9.1	12.5	16.9	17.1	16.9	15.8
50%	9.9	13.6	18.1	18.3	18.1	17.0
75%	10.8	14.7	19.4	19.6	19.4	18.2
97.5%	12.7	17.1	21.9	22.1	21.9	20.6
ME	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	9.2	15.3	37.4	39.7	37.4	33.2
25%	10.9	17.2	41.7	43.3	41.7	35.8
50%	11.9	18.5	44.5	46.0	44.5	38.0
75%	13.0	19.8	47.5	48.8	47.5	40.3
97.5%	15.5	21.9	52.5	52.8	52.5	43.3
MD	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	7.8	11.9	24.5	25.8	24.5	22.0
25%	8.8	13.1	26.8	27.6	26.8	23.5
50%	9.4	13.8	28.2	28.9	28.2	24.5
75%	10.0	14.5	29.7	30.3	29.7	25.6
97.5%	11.3	15.7	32.1	32.4	32.1	27.2
MA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	8.6	13.9	32.5	34.5	32.5	28.8
25%	10.0	15.7	36.6	38.0	36.6	31.7
50%	11.0	16.8	39.2	40.3	39.2	33.5
75%	11.9	17.9	41.7	42.7	41.7	35.4
97.5%	13.9	19.9	46.4	47.0	46.4	38.7
MI	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	9.7	15.6	36.0	37.9	36.0	31.7
25%	11.5	17.8	40.9	42.3	40.9	35.2
50%	12.6	19.1	44.0	45.5	44.0	37.8
75%	13.7	20.6	47.4	48.8	47.4	40.4
97.5%	16.2	23.2	53.4	54.0	53.4	44.6
MN	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	11.8	19.5	47.0	49.6	47.0	41.4
25%	14.2	22.3	53.5	55.4	53.5	46.0
50%	15.6	24.0	57.6	59.4	57.6	49.2
75%	17.1	25.9	62.0	63.5	62.0	52.5
97.5%	20.7	29.2	69.3	70.2	69.3	57.7
MS	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	8.2	11.6	17.8	18.2	17.8	16.3
25%	9.6	13.4	20.3	20.8	20.3	18.6
50%	10.4	14.5	21.8	22.2	21.8	20.0
75%	11.3	15.7	23.3	23.7	23.3	21.3
97.5%	13.3	18.0	26.2	26.4	26.2	23.8

MO	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	8.9	13.2	25.2	26.3	25.2	22.7
25%	10.1	14.8	28.3	29.2	28.3	25.0
50%	10.8	15.7	30.1	30.9	30.1	26.5
75%	11.6	16.6	32.0	32.7	32.0	28.0
97.5%	13.2	18.3	35.5	35.9	35.5	30.6
MT	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	9.8	16.2	39.1	41.4	39.1	34.5
25%	11.7	18.4	44.3	46.0	44.3	38.1
50%	12.9	19.8	47.6	48.9	47.6	40.5
75%	14.1	21.3	50.9	52.3	50.9	43.2
97.5%	16.7	24.0	56.9	57.8	56.9	47.5
NE	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	9.5	15.0	32.3	34.3	32.3	29.0
25%	10.8	16.5	35.6	36.9	35.6	31.0
50%	11.6	17.4	37.5	38.7	37.5	32.5
75%	12.5	18.3	39.6	40.5	39.6	33.9
97.5%	14.2	19.9	42.9	43.2	42.9	36.0
NV	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	7.7	11.6	23.4	24.5	23.4	20.9
25%	9.2	13.5	26.7	27.4	26.7	23.5
50%	10.1	14.7	28.8	29.6	28.8	25.3
75%	11.0	15.9	31.1	31.8	31.1	27.1
97.5%	13.0	18.3	34.7	35.1	34.7	30.0
NH	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	9.1	14.9	35.0	37.3	35.0	31.2
25%	10.5	16.5	38.7	40.2	38.7	33.4
50%	11.4	17.5	41.0	42.3	41.0	35.1
75%	12.3	18.5	43.3	44.4	43.3	36.8
97.5%	14.4	20.3	47.1	47.5	47.1	39.1
NJ	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	8.4	13.1	28.8	30.5	28.8	25.8
25%	9.6	14.6	31.7	32.8	31.7	27.6
50%	10.3	15.4	33.4	34.4	33.4	28.9
75%	11.1	16.2	35.3	36.1	35.3	30.2
97.5%	12.7	17.6	38.4	38.6	38.4	32.2
NM	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	7.8	12.0	24.8	25.8	24.8	22.0
25%	9.2	13.7	27.9	28.8	27.9	24.5
50%	10.1	14.8	29.9	30.6	29.9	26.0
75%	10.9	15.8	31.8	32.6	31.8	27.7
97.5%	12.7	18.0	35.6	36.1	35.6	30.6
NY	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	7.8	12.4	28.3	29.5	28.3	24.8
25%	9.3	14.4	32.8	34.0	32.8	28.3
50%	10.3	15.7	36.2	37.3	36.2	31.0
75%	11.4	17.2	39.7	40.7	39.7	33.9
97.5%	13.8	19.6	45.5	46.0	45.5	38.1

NC	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	7.5	11.0	20.2	21.0	20.2	18.3
25%	8.4	12.1	22.1	22.7	22.1	19.7
50%	8.9	12.8	23.2	23.7	23.2	20.5
75%	9.5	13.5	24.3	24.7	24.3	21.4
97.5%	10.7	14.8	26.2	26.5	26.2	22.9
ND	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	12.8	21.0	51.1	54.6	51.1	45.5
25%	15.0	23.6	57.1	59.2	57.1	48.9
50%	16.3	25.1	60.6	62.6	60.6	51.7
75%	17.8	26.7	64.3	66.1	64.3	54.6
97.5%	20.9	29.6	70.6	71.1	70.6	58.4
OH	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	8.2	13.0	28.5	30.1	28.5	25.4
25%	9.5	14.5	31.3	32.4	31.3	27.2
50%	10.2	15.3	33.0	34.0	33.0	28.6
75%	11.0	16.1	34.9	35.6	34.9	29.9
97.5%	12.5	17.6	38.0	38.1	38.0	31.8
OK	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	8.7	12.8	23.4	24.5	23.4	21.2
25%	9.8	14.2	25.6	26.4	25.6	23.0
50%	10.4	15.0	26.9	27.5	26.9	23.9
75%	11.1	15.8	28.2	28.7	28.2	24.9
97.5%	12.5	17.2	30.6	30.8	30.6	26.7
OR	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	5.8	9.4	22.3	23.3	22.3	19.4
25%	7.1	11.1	25.8	26.7	25.8	22.2
50%	7.9	12.1	28.4	29.3	28.4	24.3
75%	8.8	13.3	31.1	31.9	31.1	26.5
97.5%	10.5	15.3	35.7	36.2	35.7	29.9
PA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	7.4	11.6	25.3	26.6	25.3	22.5
25%	8.7	13.2	28.6	29.5	28.6	24.7
50%	9.5	14.3	31.1	32.1	31.1	26.9
75%	10.4	15.3	33.8	34.8	33.8	29.1
97.5%	12.1	17.3	37.7	38.1	37.7	31.7
RI	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	7.5	12.2	28.1	29.9	28.1	25.2
25%	8.7	13.5	31.1	32.2	31.1	26.9
50%	9.4	14.3	32.8	33.8	32.8	28.1
75%	10.2	15.1	34.5	35.4	34.5	29.4
97.5%	11.7	16.5	37.8	37.9	37.8	31.3
SC	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	7.1	10.3	17.0	17.5	17.0	15.5
25%	8.2	11.6	19.1	19.6	19.1	17.3
50%	8.8	12.3	20.3	20.8	20.3	18.3
75%	9.4	13.1	21.7	22.1	21.7	19.4
97.5%	10.7	14.5	24.1	24.4	24.1	21.4

SD	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	10.7	17.1	39.5	41.7	39.5	34.9
25%	12.5	19.4	44.6	46.4	44.6	38.6
50%	13.6	20.7	47.7	49.1	47.7	40.9
75%	14.8	22.1	51.0	52.2	51.0	43.4
97.5%	17.3	24.7	56.9	57.3	56.9	47.6
TN	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	7.7	11.1	19.9	20.5	19.9	17.9
25%	8.8	12.6	22.2	22.8	22.2	19.9
50%	9.4	13.4	23.7	24.2	23.7	21.1
75%	10.2	14.3	25.2	25.6	25.2	22.3
97.5%	11.6	16.0	27.6	27.9	27.6	24.2
TX	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	6.8	9.4	13.6	13.8	13.6	12.6
25%	9.2	12.8	18.8	19.1	18.8	17.4
50%	10.8	15.1	22.3	22.7	22.3	20.6
75%	12.7	17.7	26.3	26.8	26.3	24.0
97.5%	16.2	22.5	33.9	34.4	33.9	30.7
UT	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	8.4	13.4	29.6	31.3	29.6	26.4
25%	9.6	14.8	32.6	33.7	32.6	28.3
50%	10.4	15.7	34.4	35.4	34.4	29.7
75%	11.2	16.5	36.3	37.1	36.3	31.0
97.5%	12.9	18.0	39.5	39.7	39.5	33.1
VT	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	9.1	14.8	35.1	37.2	35.1	31.2
25%	10.5	16.5	38.8	40.3	38.8	33.5
50%	11.4	17.5	41.0	42.2	41.0	35.1
75%	12.4	18.5	43.3	44.4	43.3	36.8
97.5%	14.3	20.3	47.4	47.6	47.4	39.2
VA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	7.3	11.0	21.6	22.5	21.6	19.4
25%	8.5	12.4	24.5	25.3	24.5	21.6
50%	9.1	13.3	26.3	27.0	26.3	23.0
75%	9.8	14.1	28.3	28.9	28.3	24.5
97.5%	11.3	15.7	31.8	32.2	31.8	27.2
WA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	5.7	8.9	20.6	21.4	20.6	17.9
25%	7.6	11.7	27.4	28.2	27.4	23.4
50%	9.0	13.9	32.8	33.9	32.8	28.2
75%	10.7	16.3	38.5	39.7	38.5	32.8
97.5%	13.8	20.2	48.3	49.2	48.3	40.7
WV	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	7.6	11.6	23.9	25.2	23.9	21.5
25%	8.6	12.8	26.2	27.1	26.2	23.0
50%	9.2	13.5	27.6	28.4	27.6	24.1
75%	9.8	14.2	29.1	29.7	29.1	25.1
97.5%	11.2	15.4	31.5	31.7	31.5	26.7

WI	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	12.3	19.9	49.0	51.8	49.0	42.9
25%	14.7	23.2	56.4	58.3	56.4	48.2
50%	16.3	25.3	61.5	63.4	61.5	52.4
75%	18.2	27.6	66.8	68.7	66.8	56.6
97.5%	21.9	31.4	75.7	76.8	75.7	63.0
WY	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	8.7	14.2	33.5	35.4	33.5	29.6
25%	10.2	15.9	37.6	39.1	37.6	32.5
50%	11.1	17.1	40.1	41.4	40.1	34.3
75%	12.1	18.2	42.8	43.9	42.8	36.4
97.5%	14.3	20.4	47.9	48.3	47.9	39.9
USA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	8.0	12.4	26.0	27.2	26.0	23.1
25%	9.4	14.1	29.5	30.4	29.5	25.7
50%	10.2	15.1	31.7	32.6	31.7	27.5
75%	11.0	16.1	34.0	34.8	34.0	29.3
97.5%	12.8	18.1	38.1	38.6	38.1	32.5

Appendix I. Annual Operating Cost Output Data for Each State

STATE	ANNUAL OPERATING COST ($/yr)					
AL	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$482	$684	$694	$653	$832	$991
25%	$570	$800	$812	$762	$960	$1,141
50%	$622	$873	$880	$829	$1,038	$1,229
75%	$681	$947	$952	$899	$1,118	$1,320
97.5%	$808	$1,096	$1,100	$1,038	$1,281	$1,498
AZ	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$513	$739	$669	$708	$972	$1,218
25%	$609	$875	$780	$831	$1,136	$1,405
50%	$669	$948	$846	$901	$1,225	$1,513
75%	$732	$1,031	$917	$975	$1,320	$1,626
97.5%	$861	$1,180	$1,053	$1,125	$1,512	$1,840
AR	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$503	$720	$634	$721	$961	$1,110
25%	$571	$814	$749	$809	$1,076	$1,232
50%	$614	$869	$812	$860	$1,144	$1,299
75%	$658	$924	$882	$915	$1,213	$1,370
97.5%	$752	$1,027	$1,008	$1,010	$1,338	$1,497
CA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$280	$385	$314	$319	$443	$664
25%	$445	$623	$521	$512	$708	$1,041
50%	$548	$776	$649	$643	$887	$1,320
75%	$665	$941	$790	$777	$1,084	$1,637
97.5%	$910	$1,277	$1,059	$1,035	$1,463	$2,259
CO	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$493	$795	$680	$832	$1,287	$1,616
25%	$588	$913	$780	$968	$1,493	$1,822
50%	$645	$981	$838	$1,048	$1,621	$1,947
75%	$706	$1,058	$902	$1,126	$1,749	$2,075
97.5%	$833	$1,198	$1,014	$1,273	$2,000	$2,317
CT	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$707	$1,089	$678	$855	$1,217	$2,124
25%	$845	$1,283	$831	$988	$1,412	$2,457
50%	$934	$1,399	$926	$1,068	$1,543	$2,679
75%	$1,029	$1,520	$1,027	$1,152	$1,672	$2,909
97.5%	$1,228	$1,742	$1,225	$1,308	$1,924	$3,302

LEGEND	
GSHP	Ground Source Heat Pump (Vertical Closed-Loop)
ASHP	Air Source Heat Pump
AC/NG	Air-Cooled Air Conditioning with Natural Gas Furnace
AC/Oil	Air-Cooled Air Conditioning with Heating Fuel Oil Furnace
AC/LPG	Air-Cooled Air Conditioning with Liquid Petroleum Gas Furnace
AC/Elec	Air-Cooled Air Conditioning with Electrical Resistant Heating

DE	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$462	$701	$791	$756	$1,116	$1,276
25%	$567	$842	$1,021	$862	$1,266	$1,512
50%	$627	$924	$1,211	$918	$1,350	$1,651
75%	$689	$999	$1,430	$974	$1,437	$1,775
97.5%	$813	$1,139	$1,851	$1,083	$1,606	$1,983
FL	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$459	$619	$621	$618	$636	$646
25%	$557	$758	$758	$754	$780	$794
50%	$616	$840	$842	$838	$866	$886
75%	$683	$928	$934	$930	$962	$985
97.5%	$827	$1,093	$1,108	$1,103	$1,144	$1,173
GA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$418	$600	$525	$597	$769	$923
25%	$502	$715	$664	$701	$904	$1,076
50%	$551	$781	$743	$764	$980	$1,164
75%	$604	$850	$827	$831	$1,063	$1,257
97.5%	$715	$985	$976	$965	$1,217	$1,441
ID	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$316	$498	$545	$665	$1,020	$995
25%	$369	$568	$635	$778	$1,204	$1,113
50%	$401	$609	$690	$845	$1,312	$1,186
75%	$437	$651	$745	$911	$1,428	$1,260
97.5%	$513	$736	$851	$1,037	$1,637	$1,402
IL	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$533	$822	$733	$734	$1,024	$1,522
25%	$676	$1,008	$947	$889	$1,244	$1,856
50%	$758	$1,128	$1,074	$988	$1,386	$2,086
75%	$851	$1,256	$1,213	$1,091	$1,538	$2,323
97.5%	$1,038	$1,486	$1,479	$1,273	$1,803	$2,726
IN	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$471	$733	$642	$735	$1,019	$1,396
25%	$551	$831	$746	$834	$1,174	$1,546
50%	$595	$888	$801	$893	$1,270	$1,635
75%	$643	$943	$859	$952	$1,367	$1,731
97.5%	$743	$1,046	$969	$1,060	$1,546	$1,886
IA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$639	$991	$842	$906	$1,275	$1,912
25%	$758	$1,159	$1,055	$1,053	$1,505	$2,200
50%	$840	$1,268	$1,189	$1,146	$1,654	$2,413
75%	$928	$1,391	$1,338	$1,250	$1,822	$2,654
97.5%	$1,117	$1,599	$1,611	$1,427	$2,127	$2,994
KS	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$516	$783	$762	$766	$1,033	$1,405
25%	$627	$939	$927	$906	$1,248	$1,680
50%	$699	$1,038	$1,027	$1,001	$1,394	$1,873
75%	$776	$1,145	$1,141	$1,101	$1,556	$2,083
97.5%	$936	$1,339	$1,355	$1,280	$1,845	$2,425

KY	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$362	$540	$589	$609	$819	$956
25%	$423	$625	$692	$698	$957	$1,089
50%	$460	$672	$752	$750	$1,041	$1,169
75%	$499	$721	$816	$806	$1,133	$1,253
97.5%	$578	$820	$936	$912	$1,302	$1,403
LA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$523	$722	$708	$683	$798	$920
25%	$631	$868	$848	$823	$945	$1,097
50%	$699	$960	$944	$915	$1,036	$1,201
75%	$773	$1,055	$1,037	$1,003	$1,130	$1,305
97.5%	$928	$1,251	$1,223	$1,191	$1,321	$1,517
ME	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$884	$1,426	$491	$960	$1,463	$3,045
25%	$1,079	$1,688	$822	$1,098	$1,675	$3,527
50%	$1,190	$1,841	$1,023	$1,177	$1,808	$3,790
75%	$1,311	$1,995	$1,203	$1,263	$1,943	$4,069
97.5%	$1,570	$2,269	$1,500	$1,414	$2,189	$4,523
MD	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$445	$664	$752	$700	$1,021	$1,203
25%	$539	$796	$877	$788	$1,149	$1,429
50%	$597	$879	$952	$836	$1,224	$1,567
75%	$656	$961	$1,026	$886	$1,301	$1,700
97.5%	$781	$1,096	$1,167	$979	$1,443	$1,929
MA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$690	$1,103	$929	$884	$1,318	$2,229
25%	$849	$1,318	$1,097	$1,009	$1,505	$2,657
50%	$944	$1,449	$1,201	$1,080	$1,616	$2,892
75%	$1,051	$1,581	$1,308	$1,155	$1,739	$3,136
97.5%	$1,256	$1,832	$1,516	$1,294	$1,971	$3,598
MI	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$727	$1,155	$710	$885	$1,265	$2,353
25%	$863	$1,331	$826	$1,035	$1,503	$2,646
50%	$945	$1,438	$890	$1,120	$1,640	$2,845
75%	$1,037	$1,555	$961	$1,212	$1,787	$3,058
97.5%	$1,230	$1,769	$1,093	$1,373	$2,077	$3,403
MN	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$692	$1,132	$895	$1,053	$1,557	$2,394
25%	$839	$1,319	$1,108	$1,244	$1,875	$2,719
50%	$931	$1,435	$1,242	$1,352	$2,059	$2,931
75%	$1,030	$1,555	$1,380	$1,470	$2,252	$3,156
97.5%	$1,249	$1,779	$1,656	$1,680	$2,613	$3,552
MS	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$505	$710	$676	$678	$847	$1,009
25%	$593	$830	$798	$794	$984	$1,155
50%	$649	$902	$875	$865	$1,065	$1,244
75%	$706	$980	$953	$943	$1,152	$1,336
97.5%	$834	$1,129	$1,105	$1,084	$1,316	$1,504

MO	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$445	$661	$718	$714	$948	$1,116
25%	$547	$799	$842	$821	$1,096	$1,350
50%	$607	$881	$910	$880	$1,181	$1,485
75%	$672	$963	$984	$943	$1,273	$1,622
97.5%	$796	$1,121	$1,127	$1,060	$1,447	$1,873
MT	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$521	$847	$796	$880	$1,407	$1,768
25%	$648	$1,013	$950	$1,050	$1,663	$2,096
50%	$724	$1,115	$1,047	$1,151	$1,823	$2,282
75%	$804	$1,217	$1,144	$1,255	$1,992	$2,476
97.5%	$975	$1,422	$1,335	$1,443	$2,301	$2,831
NE	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$476	$743	$651	$794	$1,109	$1,421
25%	$565	$855	$768	$904	$1,284	$1,612
50%	$615	$922	$839	$967	$1,384	$1,721
75%	$669	$989	$911	$1,026	$1,491	$1,833
97.5%	$788	$1,114	$1,052	$1,131	$1,677	$2,036
NV	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$489	$728	$592	$720	$1,061	$1,301
25%	$587	$861	$701	$854	$1,247	$1,502
50%	$650	$945	$766	$936	$1,358	$1,629
75%	$717	$1,029	$837	$1,021	$1,480	$1,756
97.5%	$857	$1,198	$978	$1,185	$1,717	$1,983
NH	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$953	$1,548	$1,023	$974	$1,436	$3,220
25%	$1,118	$1,749	$1,208	$1,095	$1,623	$3,544
50%	$1,219	$1,870	$1,315	$1,162	$1,729	$3,748
75%	$1,323	$1,993	$1,420	$1,230	$1,839	$3,952
97.5%	$1,561	$2,208	$1,627	$1,357	$2,050	$4,286
NJ	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$668	$1,030	$534	$841	$1,230	$1,993
25%	$773	$1,171	$734	$938	$1,383	$2,223
50%	$838	$1,251	$849	$994	$1,474	$2,351
75%	$909	$1,332	$966	$1,051	$1,566	$2,489
97.5%	$1,056	$1,482	$1,172	$1,149	$1,741	$2,717
NM	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$509	$776	$561	$688	$1,017	$1,416
25%	$605	$899	$684	$797	$1,175	$1,602
50%	$664	$974	$765	$862	$1,274	$1,717
75%	$726	$1,053	$845	$930	$1,375	$1,842
97.5%	$856	$1,207	$998	$1,065	$1,572	$2,069
NY	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$870	$1,369	$775	$830	$1,242	$2,710
25%	$1,088	$1,677	$1,007	$976	$1,468	$3,304
50%	$1,230	$1,871	$1,153	$1,067	$1,614	$3,688
75%	$1,378	$2,082	$1,322	$1,163	$1,770	$4,099
97.5%	$1,716	$2,493	$1,669	$1,337	$2,063	$4,848

NC	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$442	$651	$659	$646	$872	$1,077
25%	$504	$729	$748	$722	$978	$1,182
50%	$540	$774	$796	$765	$1,036	$1,241
75%	$577	$819	$848	$808	$1,097	$1,300
97.5%	$650	$903	$940	$885	$1,214	$1,409
ND	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$701	$1,133	$910	$1,130	$1,681	$2,437
25%	$831	$1,304	$1,125	$1,309	$1,978	$2,722
50%	$912	$1,408	$1,253	$1,411	$2,151	$2,890
75%	$997	$1,512	$1,383	$1,515	$2,337	$3,068
97.5%	$1,185	$1,690	$1,623	$1,698	$2,678	$3,367
OH	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$586	$914	$775	$757	$1,045	$1,765
25%	$677	$1,031	$894	$856	$1,197	$1,944
50%	$732	$1,098	$962	$911	$1,283	$2,051
75%	$790	$1,166	$1,032	$966	$1,377	$2,160
97.5%	$910	$1,290	$1,161	$1,071	$1,549	$2,349
OK	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$446	$644	$669	$695	$897	$1,050
25%	$542	$782	$772	$793	$1,025	$1,257
50%	$599	$861	$829	$847	$1,096	$1,380
75%	$657	$937	$888	$905	$1,172	$1,493
97.5%	$776	$1,077	$1,000	$1,010	$1,315	$1,682
OR	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$279	$449	$482	$560	$923	$925
25%	$342	$531	$605	$676	$1,113	$1,068
50%	$381	$583	$693	$748	$1,235	$1,170
75%	$423	$639	$792	$829	$1,377	$1,272
97.5%	$510	$738	$996	$981	$1,635	$1,448
PA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$435	$674	$712	$682	$1,028	$1,289
25%	$522	$790	$829	$784	$1,195	$1,493
50%	$578	$864	$904	$852	$1,302	$1,628
75%	$635	$944	$984	$922	$1,422	$1,781
97.5%	$758	$1,091	$1,129	$1,036	$1,624	$2,031
RI	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$630	$990	$861	$790	$1,147	$1,986
25%	$789	$1,216	$1,006	$890	$1,306	$2,413
50%	$885	$1,345	$1,089	$947	$1,394	$2,659
75%	$983	$1,480	$1,173	$1,001	$1,480	$2,894
97.5%	$1,187	$1,701	$1,326	$1,101	$1,641	$3,282
SC	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$407	$584	$611	$592	$763	$875
25%	$472	$669	$700	$676	$871	$999
50%	$509	$716	$752	$721	$932	$1,065
75%	$549	$768	$804	$771	$998	$1,136
97.5%	$631	$860	$908	$860	$1,123	$1,272

SD	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$657	$1,047	$793	$947	$1,366	$2,120
25%	$775	$1,199	$985	$1,095	$1,605	$2,387
50%	$848	$1,289	$1,097	$1,181	$1,745	$2,550
75%	$925	$1,382	$1,208	$1,268	$1,900	$2,717
97.5%	$1,087	$1,559	$1,413	$1,433	$2,194	$3,011
TN	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$446	$644	$617	$630	$804	$1,036
25%	$519	$743	$722	$725	$924	$1,175
50%	$562	$802	$783	$777	$992	$1,257
75%	$610	$860	$842	$832	$1,064	$1,342
97.5%	$710	$975	$963	$935	$1,207	$1,494
TX	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$439	$615	$557	$578	$696	$815
25%	$601	$842	$766	$794	$971	$1,144
50%	$714	$999	$913	$943	$1,143	$1,358
75%	$838	$1,169	$1,072	$1,107	$1,335	$1,591
97.5%	$1,086	$1,497	$1,388	$1,424	$1,720	$2,041
UT	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$404	$643	$537	$711	$1,076	$1,250
25%	$472	$724	$610	$822	$1,240	$1,388
50%	$511	$773	$648	$884	$1,338	$1,463
75%	$553	$821	$688	$944	$1,443	$1,541
97.5%	$644	$909	$763	$1,059	$1,630	$1,681
VT	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$873	$1,410	$884	$966	$1,427	$2,906
25%	$1,065	$1,657	$992	$1,088	$1,616	$3,361
50%	$1,169	$1,797	$1,055	$1,156	$1,723	$3,604
75%	$1,287	$1,935	$1,121	$1,225	$1,832	$3,852
97.5%	$1,521	$2,196	$1,253	$1,352	$2,050	$4,297
VA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$387	$580	$633	$625	$892	$1,019
25%	$452	$662	$736	$713	$1,031	$1,154
50%	$489	$711	$802	$763	$1,112	$1,235
75%	$531	$764	$872	$816	$1,198	$1,322
97.5%	$616	$857	$1,009	$920	$1,369	$1,486
WA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$263	$408	$437	$533	$874	$825
25%	$355	$545	$581	$719	$1,184	$1,092
50%	$422	$647	$690	$857	$1,422	$1,309
75%	$498	$760	$813	$1,012	$1,684	$1,532
97.5%	$648	$960	$1,035	$1,290	$2,181	$1,922
WV	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$389	$591	$622	$651	$959	$1,093
25%	$446	$662	$693	$731	$1,080	$1,191
50%	$479	$703	$732	$773	$1,149	$1,254
75%	$515	$744	$772	$816	$1,221	$1,317
97.5%	$587	$818	$847	$893	$1,357	$1,421

WI	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$693	$1,115	$989	$1,082	$1,615	$2,408
25%	$838	$1,323	$1,214	$1,289	$1,969	$2,754
50%	$934	$1,452	$1,355	$1,420	$2,174	$3,000
75%	$1,048	$1,585	$1,508	$1,561	$2,405	$3,257
97.5%	$1,266	$1,835	$1,831	$1,802	$2,835	$3,695
WY	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$430	$694	$556	$762	$1,193	$1,451
25%	$506	$793	$691	$899	$1,411	$1,610
50%	$554	$852	$777	$981	$1,541	$1,716
75%	$608	$912	$870	$1,062	$1,677	$1,826
97.5%	$723	$1,032	$1,044	$1,214	$1,955	$2,029
USA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$514	$789	$685	$734	$1,053	$1,453
25%	$612	$920	$813	$847	$1,221	$1,678
50%	$670	$996	$892	$914	$1,322	$1,813
75%	$733	$1,076	$974	$982	$1,433	$1,951
97.5%	$864	$1,229	$1,129	$1,110	$1,642	$2,207

Appendix J. Total Life Cycle Cost Output Data for Each State

STATE	LIFE CYCLE COST ($/50yr evalution Period)					
AL	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$40,417	$54,702	$49,079	$47,198	$56,119	$64,429
25%	$45,398	$62,146	$56,046	$54,080	$63,704	$72,994
50%	$48,340	$66,380	$60,463	$58,201	$68,374	$78,021
75%	$51,509	$70,956	$64,903	$62,562	$73,099	$83,256
97.5%	$58,344	$79,683	$73,890	$71,190	$82,543	$93,617
AZ	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$40,962	$55,843	$46,515	$49,252	$62,455	$74,637
25%	$46,198	$63,758	$53,162	$56,002	$71,248	$84,965
50%	$49,377	$68,230	$57,225	$60,262	$76,167	$90,877
75%	$52,652	$72,829	$61,566	$64,725	$81,580	$96,939
97.5%	$59,535	$82,079	$70,067	$73,896	$92,507	$108,912
AR	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$41,304	$56,287	$46,121	$50,430	$62,177	$69,996
25%	$45,480	$62,546	$53,097	$56,060	$69,501	$77,157
50%	$47,889	$66,243	$57,003	$59,612	$73,576	$81,530
75%	$50,361	$70,076	$61,255	$63,381	$77,741	$86,113
97.5%	$55,515	$76,933	$69,200	$70,340	$85,761	$94,750
CA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$31,558	$34,061	$30,388	$30,575	$37,693	$48,106
25%	$40,130	$47,022	$41,681	$41,601	$51,269	$67,876
50%	$45,477	$54,936	$48,501	$48,640	$60,496	$82,342
75%	$51,404	$63,392	$56,116	$55,770	$70,570	$98,382
97.5%	$63,761	$80,243	$70,978	$69,772	$91,320	$129,474
CO	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$38,140	$51,614	$44,891	$53,380	$76,242	$92,402
25%	$43,190	$57,918	$51,015	$60,818	$87,052	$103,400
50%	$46,249	$61,632	$54,449	$65,092	$93,778	$109,981
75%	$49,457	$65,588	$58,191	$69,569	$100,402	$116,805
97.5%	$55,979	$72,852	$65,233	$78,210	$113,552	$129,091
CT	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$53,881	$71,063	$48,869	$57,662	$75,770	$121,524
25%	$61,404	$81,263	$57,597	$65,567	$86,887	$139,126
50%	$65,894	$87,163	$62,811	$70,306	$93,730	$150,315
75%	$70,959	$93,488	$68,512	$75,166	$100,747	$161,982
97.5%	$81,208	$105,080	$79,244	$84,004	$113,915	$181,785

LEGEND

GSHP	Ground Source Heat Pump (Vertical Closed-Loop)
ASHP	Air Source Heat Pump
AC/NG	Air-Cooled Air Conditioning with Natural Gas Furnace
AC/Oil	Air-Cooled Air Conditioning with Heating Fuel Oil Furnace
AC/LPG	Air-Cooled Air Conditioning with Liquid Petroleum Gas Furnace
AC/Elec	Air-Cooled Air Conditioning with Electrical Resistant Heating

DE	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$40,763	$50,374	$54,091	$52,130	$69,830	$78,276
25%	$46,593	$58,261	$66,833	$58,219	$78,507	$91,010
50%	$49,883	$62,569	$76,385	$61,792	$83,302	$98,239
75%	$53,150	$66,812	$87,803	$65,774	$88,272	$104,939
97.5%	$60,074	$74,588	$108,387	$73,098	$97,775	$116,512
FL	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$40,226	$51,684	$45,232	$45,256	$45,922	$47,003
25%	$45,714	$59,544	$53,226	$53,266	$54,332	$55,256
50%	$48,958	$64,466	$58,053	$58,111	$59,328	$60,670
75%	$52,490	$69,743	$63,196	$63,218	$64,650	$66,121
97.5%	$60,013	$79,290	$72,712	$72,585	$74,328	$76,888
GA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$34,552	$42,286	$37,346	$41,161	$49,644	$57,826
25%	$39,053	$48,409	$45,233	$47,198	$57,145	$66,083
50%	$41,672	$51,922	$49,556	$50,837	$61,484	$70,759
75%	$44,513	$55,733	$54,194	$54,947	$66,009	$75,684
97.5%	$50,455	$63,158	$62,971	$62,395	$74,938	$85,570
ID	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$28,326	$36,424	$38,418	$44,763	$62,580	$61,001
25%	$31,413	$40,704	$43,894	$51,417	$72,542	$67,969
50%	$33,310	$43,198	$47,207	$55,218	$78,460	$72,206
75%	$35,227	$45,691	$50,534	$59,204	$84,496	$76,454
97.5%	$39,457	$50,513	$57,227	$66,884	$95,557	$84,272
IL	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$44,837	$57,014	$52,129	$52,030	$66,663	$91,537
25%	$52,388	$67,207	$63,244	$60,925	$78,301	$108,841
50%	$56,573	$73,500	$70,148	$66,206	$85,649	$120,677
75%	$61,450	$80,221	$77,470	$71,786	$93,550	$132,923
97.5%	$71,188	$92,508	$91,823	$82,444	$107,939	$152,973
IN	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$39,889	$50,940	$45,038	$49,965	$64,410	$83,313
25%	$44,389	$56,522	$51,283	$56,160	$73,149	$91,575
50%	$46,813	$59,725	$54,881	$59,718	$78,340	$96,801
75%	$49,463	$62,983	$58,515	$63,527	$83,654	$101,849
97.5%	$54,950	$69,320	$65,457	$70,593	$93,751	$110,652
IA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$47,356	$63,118	$54,940	$57,881	$76,604	$108,316
25%	$53,541	$71,959	$66,261	$66,244	$88,712	$123,603
50%	$57,694	$77,598	$73,064	$71,420	$96,529	$134,448
75%	$62,253	$83,577	$80,987	$76,832	$104,864	$146,417
97.5%	$71,690	$94,730	$95,037	$87,070	$120,066	$163,846
KS	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$40,895	$52,479	$50,768	$50,788	$64,076	$83,167
25%	$46,541	$60,781	$59,687	$58,824	$75,735	$97,536
50%	$50,273	$65,972	$65,088	$64,013	$83,534	$107,408
75%	$54,363	$71,687	$71,117	$69,495	$91,596	$117,976
97.5%	$62,574	$81,897	$82,331	$79,057	$106,914	$135,109

KY	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$32,531	$39,873	$41,167	$42,222	$52,960	$59,849
25%	$36,079	$44,714	$47,317	$47,902	$60,815	$67,404
50%	$38,251	$47,504	$51,024	$51,268	$65,595	$71,950
75%	$40,479	$50,386	$54,745	$54,741	$70,408	$76,389
97.5%	$44,835	$56,338	$62,163	$61,672	$79,847	$85,288
LA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$43,471	$56,795	$49,957	$48,855	$54,430	$61,281
25%	$49,460	$65,655	$58,359	$57,382	$63,102	$71,052
50%	$53,039	$70,883	$63,599	$62,317	$68,247	$76,665
75%	$56,972	$76,367	$69,149	$67,799	$73,779	$82,609
97.5%	$65,184	$86,799	$79,577	$78,175	$84,170	$93,805
ME	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$57,397	$82,467	$34,861	$58,067	$83,035	$162,835
25%	$67,195	$96,229	$51,761	$65,462	$94,356	$187,021
50%	$72,980	$103,947	$61,921	$69,982	$101,124	$200,323
75%	$79,063	$111,822	$70,887	$74,450	$107,941	$214,339
97.5%	$91,844	$125,700	$86,109	$82,713	$121,046	$237,413
MD	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$36,115	$46,171	$49,504	$46,819	$62,938	$72,675
25%	$41,220	$53,319	$56,438	$52,022	$70,107	$84,415
50%	$44,372	$57,667	$60,690	$55,180	$74,315	$91,574
75%	$47,545	$61,994	$64,981	$58,490	$78,721	$98,397
97.5%	$53,788	$69,364	$73,010	$64,589	$86,973	$111,049
MA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$51,517	$69,397	$60,255	$57,827	$79,940	$126,163
25%	$59,698	$80,933	$69,711	$65,301	$90,060	$147,679
50%	$64,659	$87,489	$75,230	$69,608	$96,043	$159,752
75%	$69,967	$94,441	$81,127	$74,088	$102,586	$172,208
97.5%	$80,980	$106,980	$92,238	$82,451	$115,310	$195,495
MI	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$50,760	$70,664	$47,293	$56,631	$75,824	$130,593
25%	$57,919	$79,837	$54,008	$64,905	$88,332	$145,579
50%	$62,132	$85,458	$57,918	$69,689	$95,466	$156,037
75%	$66,736	$91,163	$62,020	$74,729	$103,157	$166,248
97.5%	$76,879	$102,271	$70,065	$83,969	$118,361	$184,486
MN	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$53,711	$71,930	$57,914	$65,850	$91,017	$132,990
25%	$61,324	$82,180	$69,410	$76,473	$107,659	$149,801
50%	$66,061	$88,413	$76,214	$82,229	$117,023	$160,457
75%	$71,287	$94,374	$83,711	$88,485	$127,137	$171,904
97.5%	$82,874	$106,508	$97,891	$99,588	$145,564	$191,940
MS	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$40,894	$54,448	$46,897	$47,352	$55,520	$64,249
25%	$45,747	$61,625	$54,291	$54,211	$63,574	$72,482
50%	$48,629	$65,914	$58,633	$58,550	$68,223	$77,480
75%	$51,843	$70,616	$63,502	$63,130	$73,197	$82,647
97.5%	$58,347	$79,025	$72,516	$71,824	$82,935	$92,477

MO	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$41,763	$56,639	$52,250	$52,142	$64,033	$73,658
25%	$47,334	$64,771	$59,655	$58,743	$72,552	$85,561
50%	$50,648	$69,779	$64,069	$62,696	$77,629	$92,942
75%	$54,159	$74,820	$68,706	$67,135	$83,077	$100,757
97.5%	$61,080	$85,032	$77,758	$75,428	$93,823	$114,098
MT	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$43,642	$56,875	$52,215	$56,695	$82,918	$100,821
25%	$50,374	$66,118	$60,538	$66,056	$96,467	$117,959
50%	$54,257	$71,414	$65,746	$71,433	$104,667	$127,475
75%	$58,455	$76,695	$70,938	$76,757	$113,189	$137,300
97.5%	$67,318	$87,366	$81,134	$87,207	$129,143	$155,136
NE	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$37,442	$49,475	$44,037	$51,482	$67,286	$83,167
25%	$42,308	$55,877	$50,849	$57,777	$76,859	$93,315
50%	$44,970	$59,484	$54,783	$61,268	$82,050	$99,113
75%	$47,858	$63,157	$58,908	$64,820	$87,644	$105,057
97.5%	$54,008	$69,854	$66,852	$71,978	$97,926	$115,928
NV	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$42,433	$51,791	$43,349	$50,302	$67,496	$79,738
25%	$47,944	$59,473	$50,104	$58,377	$77,641	$90,524
50%	$51,341	$63,822	$54,203	$62,996	$83,829	$97,142
75%	$54,964	$68,359	$58,482	$67,971	$90,288	$104,044
97.5%	$62,368	$77,543	$66,856	$77,420	$103,268	$116,104
NH	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$59,053	$87,817	$62,164	$59,573	$82,300	$172,270
25%	$67,645	$97,950	$71,790	$66,159	$92,478	$188,738
50%	$72,713	$104,212	$77,407	$69,977	$98,192	$198,937
75%	$78,119	$110,532	$82,902	$73,945	$103,883	$209,638
97.5%	$89,778	$121,319	$93,815	$81,094	$114,981	$225,930
NJ	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$52,584	$68,104	$42,483	$57,302	$76,651	$115,224
25%	$58,435	$76,193	$53,454	$63,541	$85,874	$127,919
50%	$61,967	$80,529	$59,892	$67,125	$91,201	$134,735
75%	$65,826	$85,101	$66,234	$71,153	$96,241	$141,955
97.5%	$73,671	$93,364	$77,897	$79,142	$106,447	$154,624
NM	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$40,521	$52,528	$40,799	$47,129	$63,534	$83,581
25%	$45,801	$59,286	$47,838	$53,543	$72,400	$93,811
50%	$48,909	$63,278	$52,104	$57,413	$77,692	$99,974
75%	$52,218	$67,538	$56,628	$61,531	$83,120	$106,374
97.5%	$59,011	$75,867	$65,500	$69,384	$93,926	$118,694
NY	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$58,547	$82,232	$52,852	$55,856	$76,212	$150,268
25%	$69,792	$97,764	$65,310	$64,008	$88,356	$180,026
50%	$76,907	$107,821	$73,023	$68,965	$96,053	$199,389
75%	$84,521	$118,557	$81,921	$74,454	$104,292	$220,267
97.5%	$101,337	$139,107	$99,471	$84,570	$119,380	$258,174

NC	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$34,389	$43,608	$43,332	$42,613	$54,133	$64,310
25%	$37,696	$48,106	$48,326	$47,265	$59,956	$70,344
50%	$39,711	$50,658	$51,325	$49,928	$63,316	$73,653
75%	$41,723	$53,293	$54,417	$52,721	$66,767	$77,326
97.5%	$45,851	$58,374	$60,226	$57,955	$73,635	$83,820
ND	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$53,586	$78,537	$57,658	$68,946	$97,496	$134,357
25%	$60,484	$87,955	$69,666	$78,954	$112,357	$149,122
50%	$64,704	$93,749	$76,193	$84,374	$120,962	$158,024
75%	$69,066	$99,605	$82,997	$90,022	$130,587	$167,028
97.5%	$78,657	$109,583	$95,535	$100,107	$147,669	$182,798
OH	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$43,199	$57,953	$50,689	$49,958	$64,323	$100,196
25%	$48,215	$64,563	$57,637	$55,766	$72,841	$110,066
50%	$51,150	$68,142	$61,476	$59,179	$77,551	$115,851
75%	$54,196	$71,823	$65,513	$62,634	$82,568	$121,818
97.5%	$60,414	$78,780	$73,280	$69,474	$92,248	$131,790
OK	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$37,962	$52,080	$46,899	$48,424	$58,677	$66,739
25%	$43,212	$59,903	$53,269	$54,485	$66,050	$78,107
50%	$46,254	$64,315	$56,800	$57,965	$70,242	$84,424
75%	$49,390	$68,764	$60,746	$61,837	$74,649	$90,446
97.5%	$55,637	$77,172	$68,008	$69,306	$83,421	$101,555
OR	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$25,210	$32,567	$35,759	$39,785	$58,054	$57,743
25%	$28,873	$37,285	$42,779	$46,590	$68,300	$65,880
50%	$30,947	$40,003	$47,446	$50,592	$74,632	$71,362
75%	$33,216	$43,023	$52,725	$55,145	$81,781	$76,707
97.5%	$37,917	$48,666	$63,576	$63,626	$95,489	$86,290
PA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$36,967	$47,058	$48,289	$46,657	$64,424	$77,715
25%	$41,693	$53,453	$55,156	$53,186	$73,584	$88,588
50%	$44,677	$57,581	$59,609	$57,191	$79,465	$95,833
75%	$47,790	$61,641	$63,946	$61,327	$85,680	$103,587
97.5%	$54,120	$69,733	$72,372	$68,692	$96,617	$116,536
RI	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$46,976	$63,284	$56,291	$52,463	$70,694	$113,161
25%	$55,362	$75,176	$64,269	$58,802	$79,439	$134,881
50%	$60,233	$81,779	$69,169	$62,210	$84,160	$147,114
75%	$65,425	$88,592	$73,871	$65,850	$89,319	$159,201
97.5%	$75,858	$100,626	$82,591	$72,550	$98,527	$179,375
SC	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$34,853	$47,302	$43,010	$42,189	$50,846	$56,869
25%	$38,642	$52,589	$48,579	$47,475	$57,227	$64,076
50%	$40,742	$55,917	$51,970	$50,652	$61,007	$67,944
75%	$42,910	$59,341	$55,461	$54,178	$64,931	$72,220
97.5%	$47,389	$66,006	$62,422	$60,671	$72,798	$80,189

SD	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$46,921	$64,984	$51,744	$59,334	$80,499	$118,175
25%	$53,086	$73,023	$61,861	$67,705	$92,843	$132,140
50%	$56,897	$77,740	$67,814	$72,359	$100,441	$140,323
75%	$60,960	$82,626	$73,790	$76,981	$107,981	$148,831
97.5%	$69,229	$91,976	$84,285	$86,406	$123,320	$164,014
TN	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$37,779	$51,637	$44,147	$45,312	$53,876	$65,561
25%	$41,844	$57,704	$50,969	$51,175	$61,063	$73,769
50%	$44,315	$61,428	$54,573	$54,632	$65,117	$78,531
75%	$46,978	$65,411	$58,338	$58,281	$69,353	$83,406
97.5%	$52,221	$72,763	$66,181	$65,368	$77,961	$92,614
TX	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$38,960	$52,082	$42,503	$43,954	$50,102	$56,129
25%	$47,423	$64,154	$54,087	$55,841	$64,211	$73,208
50%	$53,131	$72,297	$61,824	$63,687	$73,424	$84,136
75%	$59,455	$81,165	$70,024	$72,107	$83,193	$96,254
97.5%	$71,827	$98,366	$86,599	$88,686	$102,950	$119,174
UT	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$32,391	$43,299	$37,265	$46,353	$64,923	$73,688
25%	$35,993	$47,873	$41,626	$52,882	$73,603	$80,960
50%	$38,174	$50,457	$44,267	$56,400	$78,903	$85,164
75%	$40,366	$53,278	$47,065	$60,083	$84,307	$89,490
97.5%	$45,261	$58,486	$52,553	$67,040	$94,231	$97,169
VT	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$53,640	$79,728	$53,475	$58,156	$81,255	$155,836
25%	$63,415	$92,278	$59,744	$64,835	$91,039	$178,371
50%	$68,700	$99,453	$63,231	$68,536	$96,476	$190,599
75%	$74,567	$106,496	$66,876	$72,250	$102,332	$203,225
97.5%	$86,658	$119,786	$73,878	$79,257	$113,385	$225,494
VA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$33,022	$40,968	$42,798	$42,828	$56,321	$62,718
25%	$36,707	$46,077	$49,053	$47,918	$63,754	$70,038
50%	$38,823	$48,878	$52,874	$51,139	$68,287	$74,682
75%	$41,116	$51,763	$56,823	$54,425	$73,072	$79,631
97.5%	$45,701	$57,331	$64,539	$60,782	$82,146	$88,380
WA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$25,081	$30,814	$33,376	$38,770	$56,134	$53,173
25%	$30,010	$38,077	$41,685	$49,016	$71,987	$67,357
50%	$33,418	$43,306	$47,492	$56,163	$83,865	$78,080
75%	$37,322	$49,069	$53,812	$64,115	$97,062	$89,558
97.5%	$44,805	$59,417	$65,461	$79,022	$122,224	$109,489
WV	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$33,924	$42,573	$42,891	$44,657	$60,206	$66,479
25%	$37,285	$46,974	$47,430	$49,580	$67,176	$73,009
50%	$39,224	$49,510	$50,239	$52,552	$71,266	$76,569
75%	$41,268	$52,099	$53,130	$55,720	$75,257	$80,290
97.5%	$45,536	$57,106	$59,019	$61,716	$83,329	$87,237

WI	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$53,273	$71,066	$61,219	$67,030	$93,671	$132,737
25%	$60,900	$81,742	$73,638	$77,916	$111,497	$150,602
50%	$65,826	$88,528	$81,151	$84,553	$121,764	$162,919
75%	$71,820	$95,426	$88,938	$91,892	$133,633	$176,087
97.5%	$83,296	$108,654	$105,309	$104,733	$155,027	$198,222
WY	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$33,164	$45,158	$37,895	$48,189	$70,041	$82,839
25%	$37,404	$50,658	$45,073	$55,816	$81,284	$91,405
50%	$39,888	$53,848	$49,750	$60,193	$87,975	$96,797
75%	$42,711	$57,113	$54,702	$64,622	$94,720	$102,476
97.5%	$48,618	$63,462	$63,925	$73,206	$108,976	$112,959
USA	GSHP	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	$40,904	$53,193	$46,974	$49,248	$65,558	$86,038
25%	$46,323	$60,496	$54,380	$56,237	$74,913	$97,775
50%	$49,375	$64,516	$58,910	$60,183	$80,392	$104,887
75%	$52,668	$68,848	$63,463	$64,339	$86,188	$112,129
97.5%	$59,494	$77,411	$72,343	$71,990	$97,414	$125,514

Appendix K. Payback Period of Vertical Closed-Loop GSHP Relative to Air-Cooled AC with Natural Gas Furnace Output Data for Each State

STATE	PAYBACK YEARS				
AL	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	0.1	1.3	1.2	0.8	0.5
25%	1.3	4.6	5.2	2.9	1.9
50%	2.9	7.2	8.4	4.5	3.0
75%	5.2	10.4	12.7	6.1	4.0
97.5%	12.9	23.5	37.6	10.4	6.0
AZ	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	0.1	2.9	2.0	1.1	0.6
25%	1.2	7.1	5.2	2.4	1.5
50%	2.6	10.6	7.7	3.4	2.1
75%	4.5	16.1	11.1	4.4	2.8
97.5%	10.0	80.7	32.0	7.0	4.0
AR	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	0.1	1.7	1.1	0.7	0.5
25%	1.3	5.7	4.4	2.3	1.7
50%	2.9	9.2	7.0	3.4	2.6
75%	5.0	14.6	10.1	4.7	3.5
97.5%	11.2	85.0	22.9	7.4	5.2
CA	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	6.0	6.8	6.7	2.6	1.3
25%	11.4	17.1	18.0	6.0	2.7
50%	16.4	30.9	31.7	8.8	3.9
75%	23.6	63.0	66.2	13.0	5.5
97.5%	60.4	654.3	679.3	29.4	10.5
CO	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	3.8	3.7	1.8	0.9	0.7
25%	6.3	7.8	3.8	1.7	1.3
50%	8.2	11.6	5.3	2.3	1.7
75%	10.7	18.5	7.3	3.0	2.2
97.5%	19.3	118.8	15.3	4.5	2.9
CT	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	3.2	6.5	5.3	1.9	0.7
25%	5.7	16.5	12.9	3.7	1.3
50%	7.8	30.1	21.8	5.1	1.8
75%	10.3	67.0	42.7	6.8	2.3
97.5%	18.9	625.4	387.9	11.8	3.2

LEGEND	
GSHP	Ground Source Heat Pump (Vertical Closed-Loop)
ASHP	Air Source Heat Pump
AC/NG	Air-Cooled Air Conditioning with Natural Gas Furnace
AC/Oil	Air-Cooled Air Conditioning with Heating Fuel Oil Furnace
AC/LPG	Air-Cooled Air Conditioning with Liquid Petroleum Gas Furnace
AC/Elec	Air-Cooled Air Conditioning with Electrical Resistant Heating

DE	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	5.4	1.7	3.8	1.8	1.3
25%	9.2	3.6	7.5	3.2	2.3
50%	12.5	5.4	10.5	4.4	3.2
75%	16.5	8.4	14.4	5.7	4.0
97.5%	30.3	20.9	30.0	8.5	5.6
FL	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	0.4	4.8	4.6	4.5	3.9
25%	3.9	9.4	9.3	8.6	7.7
50%	7.3	13.4	13.3	12.0	10.7
75%	12.0	20.5	20.5	17.9	15.8
97.5%	51.2	93.8	96.6	66.6	53.4
GA	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	4.2	3.3	3.0	1.8	1.2
25%	7.6	7.0	6.3	3.4	2.3
50%	10.3	10.4	9.0	4.7	3.2
75%	13.7	16.8	12.5	6.1	4.1
97.5%	28.3	127.6	27.7	9.3	5.9
ID	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	3.1	0.6	0.2	0.2	0.2
25%	6.3	2.7	1.5	0.8	1.0
50%	8.6	4.2	2.5	1.3	1.5
75%	11.4	6.1	3.6	1.9	2.1
97.5%	20.6	11.2	6.1	2.9	3.1
IL	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	3.5	2.5	3.3	1.6	0.8
25%	6.4	5.7	7.8	3.1	1.5
50%	8.8	8.8	11.9	4.5	2.1
75%	12.0	14.5	18.7	6.1	2.8
97.5%	21.9	82.1	90.8	10.4	4.1
IN	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	4.4	4.2	2.7	1.4	1.0
25%	7.8	8.7	5.9	2.8	1.8
50%	10.4	12.7	8.4	3.8	2.5
75%	13.7	19.0	11.6	5.1	3.2
97.5%	24.6	86.5	24.0	7.7	4.3
IA	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	3.0	2.2	2.5	1.1	0.6
25%	5.1	4.7	5.3	2.2	1.1
50%	6.8	7.0	7.7	3.0	1.6
75%	8.9	11.2	11.2	4.0	2.0
97.5%	16.2	77.6	38.3	6.3	2.8
KS	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	3.1	2.1	2.1	1.1	0.7
25%	5.7	4.5	4.7	2.2	1.3
50%	7.6	6.6	6.9	3.1	1.8
75%	10.0	9.5	9.8	4.1	2.4
97.5%	17.5	23.0	22.2	6.6	3.4

KY	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	4.9	2.6	2.2	1.3	1.1
25%	8.9	5.2	5.0	2.7	2.2
50%	12.1	7.4	7.0	3.7	3.0
75%	16.0	10.2	9.5	4.8	3.9
97.5%	27.9	19.2	16.1	7.3	5.4
LA	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	0.3	3.6	3.7	2.8	1.9
25%	2.5	7.5	8.0	5.6	3.8
50%	5.0	10.7	11.7	7.7	5.1
75%	8.1	16.2	18.5	10.7	6.7
97.5%	24.7	69.3	92.8	22.6	11.0
ME	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	1.9	2.8	5.3	1.9	0.5
25%	3.2	6.3	12.7	3.2	0.8
50%	4.3	11.3	22.5	4.4	1.0
75%	5.6	25.0	47.9	5.9	1.2
97.5%	10.5	232.5	524.7	13.8	1.6
MD	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	2.9	1.4	1.7	0.8	0.5
25%	5.5	3.3	4.5	1.9	1.2
50%	7.6	4.9	6.8	2.8	1.7
75%	10.0	6.9	9.8	3.6	2.3
97.5%	18.3	16.1	25.9	5.5	3.3
MA	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	3.4	3.4	4.8	1.7	0.7
25%	5.7	7.8	12.0	3.3	1.2
50%	7.6	12.1	20.6	4.7	1.6
75%	9.9	22.8	42.7	6.2	2.1
97.5%	18.3	199.7	436.5	11.1	2.9
MI	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	2.4	4.7	2.8	1.0	0.4
25%	4.2	13.1	7.0	2.2	0.8
50%	5.6	24.6	11.7	3.1	1.2
75%	7.5	55.0	22.0	4.3	1.5
97.5%	14.2	641.8	241.1	7.9	2.1
MN	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	4.3	5.3	4.7	2.1	1.3
25%	7.0	10.1	8.1	3.3	1.9
50%	9.3	15.4	11.0	4.2	2.4
75%	12.1	27.2	15.6	5.4	2.9
97.5%	23.3	224.6	48.3	8.4	3.8
MS	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	0.2	3.2	2.9	1.9	1.2
25%	1.8	6.5	6.5	3.8	2.5
50%	3.6	9.4	9.3	5.1	3.5
75%	6.1	14.0	13.7	6.7	4.4
97.5%	15.5	48.8	46.9	11.2	6.5

MO	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	0.2	3.0	3.0	1.7	1.1
25%	2.4	6.7	7.1	3.6	2.4
50%	5.3	9.5	10.2	5.0	3.3
75%	8.5	13.4	14.0	6.6	4.3
97.5%	17.1	30.9	30.1	10.3	6.1
MT	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	4.6	5.2	4.1	1.9	1.4
25%	7.6	8.9	6.8	2.8	2.1
50%	10.0	12.6	9.1	3.7	2.6
75%	13.1	18.8	12.6	4.6	3.2
97.5%	24.4	90.9	31.0	6.8	4.2
NE	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	2.9	2.1	1.3	0.7	0.5
25%	5.1	5.1	3.2	1.6	1.1
50%	6.8	7.7	4.6	2.2	1.5
75%	9.0	12.2	6.4	2.9	2.0
97.5%	15.7	64.0	12.3	4.4	2.7
NV	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	5.6	8.8	4.2	2.0	1.5
25%	9.8	18.5	8.1	3.5	2.6
50%	13.1	28.9	11.4	4.8	3.5
75%	17.1	50.3	15.9	6.1	4.4
97.5%	31.3	419.2	35.5	9.2	6.0
NH	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	1.7	2.1	2.1	0.9	0.2
25%	2.9	5.9	7.2	2.1	0.4
50%	3.7	10.8	13.6	3.2	0.6
75%	4.8	23.0	29.7	4.7	0.8
97.5%	8.9	215.3	273.0	13.6	1.2
NJ	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	3.8	5.7	5.2	1.8	0.8
25%	6.8	13.9	12.7	3.6	1.6
50%	9.1	24.7	20.1	5.1	2.2
75%	12.0	52.2	35.1	6.7	2.8
97.5%	21.3	498.5	326.9	11.0	3.7
NM	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	3.1	4.1	2.6	1.1	0.6
25%	5.9	11.1	6.6	2.4	1.4
50%	8.0	19.6	10.0	3.4	1.9
75%	10.6	41.3	14.8	4.5	2.5
97.5%	18.2	402.7	51.3	6.9	3.5
NY	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	2.3	2.3	1.9	1.5	0.3
25%	3.9	7.4	6.9	3.9	0.7
50%	5.3	13.9	13.3	6.4	1.0
75%	7.2	29.5	28.5	10.4	1.4
97.5%	13.2	294.5	331.6	58.7	2.0

NC	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	3.0	1.8	1.6	1.0	0.6
25%	5.7	4.0	4.2	2.1	1.4
50%	7.7	5.8	6.2	3.0	2.0
75%	10.3	7.9	8.5	3.9	2.6
97.5%	18.5	15.5	17.1	5.8	3.6
ND	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	0.3	5.3	4.3	2.0	1.4
25%	2.3	9.1	6.8	2.9	1.9
50%	3.9	13.1	8.8	3.6	2.3
75%	5.7	22.2	11.7	4.4	2.7
97.5%	10.9	178.8	26.9	6.6	3.4
OH	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	3.0	2.4	2.6	1.1	0.5
25%	5.3	5.8	6.8	2.6	1.1
50%	7.2	8.8	10.7	3.7	1.5
75%	9.3	14.0	17.6	5.0	2.0
97.5%	16.8	70.7	111.1	8.5	2.7
OK	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	0.1	2.5	2.0	1.2	0.7
25%	1.3	5.8	5.1	2.8	1.7
50%	2.9	8.3	7.4	3.9	2.4
75%	5.0	12.0	10.2	5.1	3.1
97.5%	10.7	32.4	22.4	8.0	4.6
OR	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	4.2	0.1	0.1	0.1	0.1
25%	7.6	1.5	1.0	0.5	0.6
50%	10.3	3.0	2.2	1.1	1.3
75%	13.9	5.0	3.8	1.7	1.9
97.5%	25.5	11.8	6.9	2.9	2.9
PA	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	4.4	2.3	2.3	1.1	0.8
25%	7.8	5.1	5.6	2.3	1.6
50%	10.5	7.3	8.3	3.3	2.3
75%	13.8	10.1	11.7	4.4	3.0
97.5%	24.6	20.6	24.0	6.6	4.2
RI	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	2.7	2.7	4.1	1.5	0.5
25%	4.9	6.9	11.5	3.2	1.0
50%	6.6	11.3	21.1	4.7	1.4
75%	8.8	22.3	45.1	6.7	1.8
97.5%	15.9	215.8	486.9	14.7	2.5
SC	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	0.1	2.1	2.1	1.3	0.8
25%	1.4	5.0	5.2	2.9	2.1
50%	3.1	7.0	7.6	4.0	2.9
75%	5.4	9.7	10.6	5.3	3.8
97.5%	12.4	19.8	22.5	8.4	5.6

SD	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	2.5	2.4	1.8	0.8	0.5
25%	4.3	5.3	4.1	1.7	0.9
50%	5.7	8.3	5.9	2.3	1.2
75%	7.4	14.8	8.5	3.0	1.5
97.5%	13.2	139.9	27.6	4.8	2.0
TN	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	0.1	2.1	1.7	1.1	0.6
25%	1.2	5.3	5.1	2.8	1.7
50%	2.7	8.1	7.8	4.1	2.4
75%	4.8	11.7	11.1	5.5	3.2
97.5%	10.8	32.1	25.2	8.8	4.7
TX	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	0.2	3.3	2.7	1.8	1.1
25%	1.7	7.7	6.5	3.8	2.5
50%	3.7	11.7	9.7	5.4	3.5
75%	6.3	19.7	15.1	7.6	4.8
97.5%	17.6	129.1	56.5	15.5	8.8
UT	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	2.9	1.9	0.6	0.4	0.3
25%	5.3	6.2	2.1	1.1	0.9
50%	7.2	10.0	3.4	1.6	1.4
75%	9.5	16.4	4.8	2.2	1.9
97.5%	17.0	102.6	8.9	3.4	2.6
VT	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	1.3	1.1	0.9	0.4	0.1
25%	2.2	4.2	4.5	1.3	0.3
50%	2.9	7.8	8.9	2.0	0.4
75%	3.8	16.9	19.2	3.0	0.6
97.5%	6.8	185.4	191.8	7.3	0.9
VA	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	4.4	2.1	2.1	1.1	0.9
25%	7.8	4.4	4.8	2.3	1.8
50%	10.5	6.3	6.8	3.1	2.5
75%	13.9	8.5	9.2	4.1	3.3
97.5%	25.3	15.6	15.9	6.0	4.6
WA	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	4.5	0.4	0.2	0.1	0.1
25%	8.1	2.9	1.4	0.8	0.9
50%	11.0	5.0	2.7	1.3	1.5
75%	15.1	7.6	4.2	1.9	2.2
97.5%	29.7	15.9	7.9	3.4	3.7
WV	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	3.8	2.1	1.4	0.8	0.7
25%	7.3	5.0	3.9	1.9	1.6
50%	10.0	7.3	5.9	2.7	2.3
75%	13.3	10.0	8.1	3.6	3.1
97.5%	24.0	17.8	13.7	5.3	4.2

WI	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	4.5	5.0	4.8	2.2	1.5
25%	7.2	8.8	7.8	3.3	2.0
50%	9.5	12.3	10.5	4.2	2.5
75%	12.6	19.2	14.4	5.2	3.0
97.5%	24.5	98.3	35.3	7.9	3.9
WY	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	3.2	2.4	1.4	0.7	0.6
25%	5.4	5.2	2.8	1.3	1.1
50%	7.1	7.9	3.9	1.8	1.5
75%	9.3	13.6	5.3	2.3	1.9
97.5%	16.8	103.2	10.0	3.4	2.5
USA	ASHP	AC/NG	AC/Oil	AC/LPG	AC/Elec
2.5%	2.9	2.5	2.0	1.0	0.5
25%	5.4	5.9	5.3	2.2	1.2
50%	7.5	9.2	7.9	3.1	1.8
75%	10.1	14.8	11.6	4.1	2.3
97.5%	18.0	89.3	35.8	6.4	3.2

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14. ABSTRACT

To sustain the United States current affluence and strength, the U.S. Government has encouraged energy conservation through executive orders, federal and local laws, and consumer education. A substantial reduction in U.S. energy consumption could be realized by using geothermal heat pumps to heat and cool buildings throughout the U.S., though initial installation cost are a deterrent. This thesis uses Monte Carlo simulation to predict energy consumption, life cycle cost and payback period for the vertical closed-loop ground source heat pump (GSHP) relative to conventional heating ventilation and air conditioning (HVAC) systems: air-source heat pumps (ASHP), air-cooled air conditioning with either natural gas, fuel oil, or liquid petroleum gas furnaces, or with electrical resistance heating. The Monte Carlo simulation is performed for a standard commercial office building within each of the 48 continental states. Regardless of the conventional HVAC system chosen, the simulation shows that for each state the GSHP has the highest probability of using less energy and having a lower operating and life cycle cost than conventional HVAC systems; however, initial installation cost are typically twice that of conventional HVAC systems and payback periods vary greatly depending on site conditions. The average 50th percentile GSHP payback period in the U.S. was 7.5 years compared against the ASHP and 9.2 years compared against the air-cooled air conditioning with natural gas furnace. However, these values vary greatly depending on location and are most sensitivity to ground thermal conductivity, utility prices, and HVAC efficiency ratings. Under the right conditions, payback for geothermal heat pumps can be much shorter and the model developed in this research can help predict energy savings and payback periods for a given site.

15. SUBJECT TERMS

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